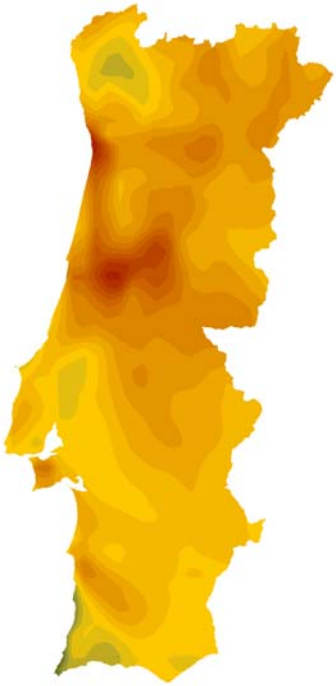
**Universidade de Aveiro** Departamento de Ambiente e Ordenamento
**2008**

**Anabela Victorino Carvalho**

# Os incêndios florestais e a qualidade do ar em cenário de alteração climática

# Forest fires and air quality under a climate change scenario



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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Ciências Aplicadas ao Ambiente, realizada sob a orientação científica da Doutora Ana Isabel Miranda, Professora Associada do Departamento de Ambiente e Ordenamento da Universidade de Aveiro

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**palavras-chave**

Alterações climáticas; incêndios florestais; índice meteorológico de risco de incêndio; modelação atmosférica; qualidade do ar

**resumo**

Os incêndios florestais e a qualidade do ar em cenário de alteração climática constituem uma das maiores ameaças ao desenvolvimento sustentável. Nestes sentido, este trabalho pretende avaliar o impacte das alterações climáticas nos incêndios florestais e na qualidade do ar.

A análise estatística de doze distritos Portugueses revelou que a meteorologia e as componentes do índice Canadiano de risco de incêndio são as variáveis que determinam os números dos incêndios florestais em Portugal. Neste âmbito, este trabalho pretendeu também caracterizar os padrões atmosféricos associados à ocorrência dos incêndios florestais. Com base numa análise estatística com desfasamento temporal (*lagged correlation*) concluiu-se que a ocorrência de grandes incêndios é precedida por transporte de ar quente e seco do centro da Península Ibérica para Portugal.

De forma a avaliar o impacte das alterações climáticas nos incêndios florestais estimou-se o índice meteorológico de risco de incêndio para o cenário SRES A2 do IPCC para duas resoluções espaciais, 12 km e 25 km. A análise permitiu concluir que num cenário de alteração climática o risco de incêndio sofrerá um agravamento significativo, principalmente nos distritos do Norte e Centro do país. Com base nesta análise e nas relações estatísticas estabelecidas entre os incêndios florestais e a meteorologia foi possível prever a área ardida e o número de incêndios em clima futuro. Os distritos de Bragança e Porto poderão ser os mais afectados em termos de aumento da área ardida. As projecções indicam que no final do século XXI a área ardida e o número de incêndios em Portugal poderão aumentar cerca de 500 % e 300 %, respectivamente, relativamente aos anos 80.

Com base nas projecções de área ardida em clima futuro estimaram-se as emissões provenientes dos incêndios florestais e avaliou-se o seu potencial impacte na qualidade do ar. O impacte das alterações climáticas e dos incêndios florestais nos níveis de ozono e partículas foi avaliado através da aplicação do sistema de modelação MM5/CHIMERE. As projecções indicam que a alteração climática contribui para o aumento dos níveis de ozono na atmosfera em cerca de 20 µg $m^{-3}$. Se a emissão dos incêndios florestais em clima futuro também for considerada poderá verificar-se uma redução das concentrações de ozono na imediação dos incêndios florestais e um aumento a jusante. Os níveis de partículas na atmosfera sofrerão aumentos mas também serão detectadas diminuições em determinadas regiões.

Neste trabalho desenvolveu-se uma ferramenta científica inovadora que ajuda a fundamentar decisões políticas e estratégias de combate e mitigação do impacte das alterações climáticas nos incêndios florestais e na qualidade do ar.

**keywords**

Climate change; forest fire activity; fire weather risk; atmospheric modelling; air quality

**abstract**

Forest fire activity and air quality under a changing climate are considered one of the main threats to sustainable development. The interaction between the climate, the forest fire activity and the air quality over Portugal is the main purpose of this study.
The relationship between the weather, the fire weather risk and the forest fire activity has been assessed for twelve districts over Portugal. Statistical significant correlations have been established among the analysed variables indicating the weather as the most important natural factor influencing forest fires in Portugal. In order to better assess the role of the regional scale atmospheric conditions in fire activity, the typical structural evolution of the atmospheric field patterns in a wildfire event was investigated by lagged analysis. The analysis pointed out that in the pre-phase of a forest fire event heated air is transported from the Iberian Peninsula's centre towards Portugal. Having in mind the important role of the atmospheric conditions on fire activity statistics over Portugal, the fire weather under the IPCC SRES A2 scenario was assessed for two spatial resolutions, 12 km and 25 km. A substantial increase on the future fire weather risk over Portugal especially in the inner districts of the North and Centre is expected.
Taking into account that the weather explains the majority of the forest fire activity in Portugal and based on the fire weather projections under future climate it was possible to forecast future area burned and number of forest fires. The projections showed a substantial increase on the area burned namely in Bragança and Porto districts. By the end of the XXI century, Portugal may face increases of approximately 500 % and 300 % for area burned and number of fires, respectively, comparatively to the 80s.
Based on the future area burned projections it was possible to estimate future fire emissions and to evaluate their impact on air quality. The MM5/CHIMERE air quality modelling system was applied to the reference and to the future climate scenarios. The projected impacts pointed that climate change alone enhances the ozone levels in the atmosphere of up to 20 µg $m^{-3}$. When forest fire emissions are also considered the ozone levels decrease in the vicinity of the forest fires but increase downwind of their locations. The particulate matter in the atmosphere will increase but decreases may also be detected.
This study constitutes an innovative scientific tool that helps to fundament strategies and policies to face and mitigate future climate change impacts on forest fire activity and air quality.

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# 1. Introduction

Nowadays climate change plays a crucial role in the international policy agenda and at national and local levels. The Intergovernmental Pannel on Climate Change (IPCC) develops fundamental actions in putting together all the developing and under developing countries trying to find answers to the most proeminent questions regarding climate change and its main challenges. In this scope the scientific community has the main aim to develop, analyse and implement the best methodologies to assess climate change and to promote the best practices to mitigate the projected impacts. In order to accomplish that, several processes should be taken into account in the scope of climate change assessment studies. The role of forest fires in the climate change context is one of the complex features that should be addressed.

There are regions of the world more vulnerable to climate change and some of those regions are also sensitive to forest fire occurrences. The way climate change drives forest dynamics, land use and forest fires is still poorly studied. Scientist from different countries namely Australia, Canada and United States of America (USA) resumed the main threats in a simple guideline known as the San Diego Declaration on Climate Change and Fire Management [Miller, 2007]. In this declaration several issues were highlighted:

- Both fire and climate regimes interact with other natural processes to drive the formation of vegetation in natural ecosystems;
- Historical fire regimes have been disrupted globally across ecosystems;
- Climate change will interact with other human activities to further change fire regimes in a different manner;

- Abrupt climate change can lead to rapid and continuous changes that disrupt natural processes and plant communities;
- Changes in climate will limit the ability to manage wildland fire and apply prescribed fire across the landscape;
- Land managers should base fire management decisions on scenarios that assume greater variability in climate and the potential for abrupt change.

This statement summarizes the main challenges that must be faced when fire activity and climate change are put together. The knowledge that is gathered on these topics and their relationship is an important tool to support decisions and fundament actions. The way climate change interacts with the forests of the world and consequently with forest fire activity is a point of debate among the scientific community.

Several features dominate the forest fires of a given region and these can be described in terms of the main temporal and spatial scales of variation. Figure 1.1 summarizes the main chacteristics of the temporal and spatial scales that are closely related to the forest fire dynamics. From a fire event to the definition of the fire regime of a given region several drivers are determinant in the characterization of these dynamics.

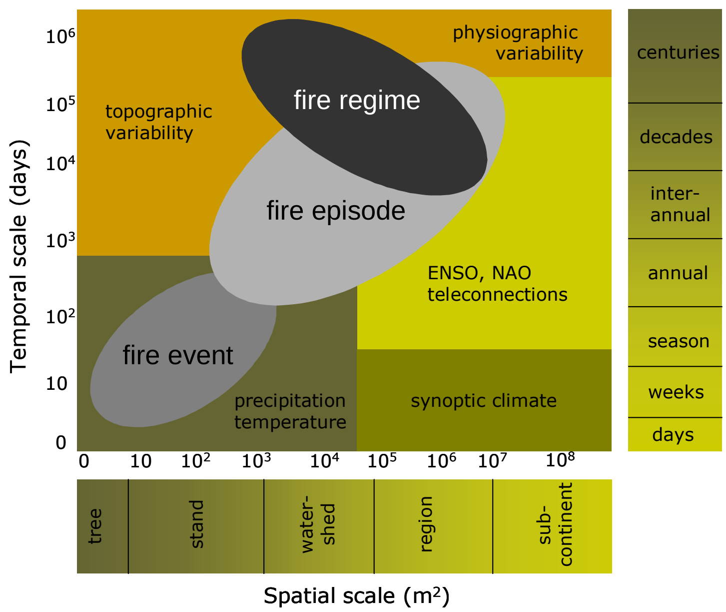



Figure 1.1 – Scheme of the scaling responses and drivers of the forest fire dynamics [Littell and Graumlich, *personnel communication*].

From the local weather conditions to the large scale weather patterns the forest fires evolve from simple events to the definition of the fire regime of a given region. The short temporal scale and the local characteristics that dominate a fire event are ruled by the local weather conditions that drive the forest fires daily variability. Additionally, the physiographic and the topographic variability that characterize the large temporal and spatial scales variations represent the broader influence of these scales on the fire regime definition.

To correctly assess the inter-connection between all analysed drivers human influence must also be considered. One of the best definitions of this relationship is given by Stephen Pyne [Pyne, 2007] who describes the area burned of a region as "a proxy of climate interacting with people". At a larger temporal and spatial scale human activities may deeply influence climate and subsequently the fire regime of a region. At local scale human activities have a remarkable impact on forest fires mainly through changes in land-use, negligente actions or simply by arson.

The influence of the human activities on climate is leading to worldwide forest fire changes and disruptions. The most recent report of the IPCC [IPCC, 2007] discusses the changing of the vegetation structure and composition due to intensified wildfire regimes driven at least partly by the 20$^{th}$ century climate change. Worldwide the wildfire regime is changing. In the USA the number of forest fires is decreasing due to fire prevention but they are becoming larger and consequently more severe. In this sense the fire suppression efforts are escalating [Miller, 2007]. Across the entire North American boreal region the total area burned from natural fires increased by a factor of 2.5 between the 1960 and 1990s, while the area burned from human-induced fires remained constant [Kasischke and Turetsky, 2006].

Recently, Europe has experienced a large number of forest fires that have caused enormous losses in terms of human lives, social disturbances, environmental damage and economic disruptions. Most of the fires in Europe take place in the Mediterranean region where over 95 % of the forest fire damage occurs [EC, 2003]. There are several features that make the landscapes of the European Mediterranean Basin different from those of the rest of Europe. These differences are mainly related to the climate, the long and intense human impact, and the role of fire. The latter is, in turn, influenced by the other two [Pausas and Vallejo, 1999]. The interaction between the humans and the fire is a complex question that drives the majority of fire occurrences in southern Europe.

Since 1980, the statistics of the annual area burned in Portugal, Spain, France, Italy and Greece, have varied considerably from one year to the next, which can be an indication of how strongly the area burned depends on weather conditions. Fire occurrence increased during the 1990s, but since 2001 the number of fires has remained more or less stable [EC, 2005]. This stabilization was possibly due to public information campaigns and improvements in the prevention and fire-fighting abilities of these countries. In Portugal, out of the last 25 years 2003 was the worst fire season, which resulted in the burning of almost 430,000 ha of forested lands and shrublands with global economic losses of 1,200 million Euros [DGRF, 2006a]. In that year the social costs were most significant with the loss of 20 human lives and the destruction of 117 houses. Due to extreme climatic conditions 2005 also recorded a very high value of area burned, approximately 325,000 ha.

Even the main reason for fire increase is probably changes in land use, climatic factors should be considered as a contributing factor. Fires tend to be concentrated in summer when temperatures are high, and air humidity and fuel moisture are low [Pausas and Vallejo, 1999]. Over Portugal and since 1972, there is a general trend towards an increase in the mean annual surface air temperature. Additionally, spring accumulated precipitation has registered a systematic reduction, accompanied by slight increases in the other seasons [Santos *et al*., 2002]. Predictions of climate warming in the Mediterranean basin indicate an increase in air temperature and a reduction in summer rainfall [Christensen and Christensen, 2007]). Although there is uncertainty on the mean and variance of the precipitation changes, all predictions suggest a future increment in water deficit. These changes would lead to an increase in water stress conditions for plants, changes in fuel conditions and increases in fire risk, with the consequent increase in ignition probability and fire propagation [Pausas and Vallejo, 1999].

Since the late 70s biomass burning has been recognized as an important source of atmospheric pollutants [Crutzen *et al*., 1979]. Several works have already discussed the importance of forest fires as a source of air pollutants [Crutzen and Andreae, 1990; Miranda *et al*., 1994; Andreae and Merlet, 2001; Amiro *et al*., 2001a; Miranda *et al*., 2005a; Miranda *et al*., 2005b] and in a changing climatic scenario this contribution can increase dramatically [Amiro *et al*., 2001b] due to larger area burned. Forest fire emissions, namely particulate matter (PM), ozone ($O_3$) precursor gases and carbon dioxide ($CO_2$), can significantly impact the ecosystems and the air quality and consequently human health [Riebau and Fox, 2001]. Particularly, they can influence plant productivity downwind of fires through enhanced ozone and aerosol concentrations [Sitch *et al*., 2007]. In a changing climate the forest fire emissions can play an important role in all these interactions.

Air quality and its potential impacts namely in the ecosystems, structures and human health is currently one of the main concerns at global, regional and local scales. Atmospheric pollutants are a transboundary problem that must be ruled by global to regional goals, as well as local measures and plans. The atmospheric $CO_2$ has increased globally by about 100 ppm (36 %) over the last 250 years, from a range of 275 to 285 ppm in the pre-industrial era (AD 1000–1750) to 379 ppm in 2005 [IPCC, 2007]. The increases in global atmospheric $CO_2$ since the industrial revolution are mainly due to $CO_2$ emissions from the combustion of fossil fuels, gas flaring and cement production. Other sources include emissions due to land use changes such as deforestation [Houghton, 2003] and biomass burning [Andreae and Merlet, 2001; Van der Werf *et al*., 2004]. As a result of the increase of ozone precursor's emissions, namely nitrogen oxides ($NO_x$), the tropospheric ozone concentrations doubled since the end of the XIX century [Brasseur *et al*., 2003]. Besides the effects of $O_3$ on human health [Weisel *et al*., 1995], tropospheric $O_3$ is the third most important anthropogenic greenhouse gas (GHG) after $CO_2$ and methane ($CH_4$) [Jacob and Gilliland, 2005]. Moreover, changes in ozone near the Earth's surface reduce plant growth as well as cause respiratory problems in humans. Sitch *et al*. [2007] identified a further indirect link between global warming and ozone: if ozone continues to increase vegetation will take up less and less of the carbon dioxide, which will leave more $CO_2$ in the atmosphere, adding to global warming.

The interaction between pollutants emissions, air quality and climate change constitutes a complex system. Major identified feedback mechanisms include the change of chemical reaction rates due to temperature change, changes in lightning emissions, and possibly further stratospheric ozone depletion due to enhanced heterogeneous processing in a cooling stratosphere. Climate change may also alter the general circulation of the atmosphere and dynamical processes on smaller scales, such as boundary layer ventilation, convection activity, and stratosphere-troposphere exchange. These considerations suggest that climate change should be considered in model studies of ozone over long periods of time [Gauss *et al*., 2006].

In the scope of climate change, the way the different implementation plans and strategies (through the development of emissions scenarios) impact the air quality at global, regional and local scales can be assessed through the application of air quality modelling systems. These modelling systems usually consist of a meteorological model and a Chemical Transport Model (CTM) and can be run together (*on-line*) or separately (*off-line*). In the scope of the research network ACCENT - Atmospheric Composition Change: an European Network, a multi-model experiment considering ozone changes between 1850 and 2000 was carried out by seven chemistry-climate models (CCM) and three chemical transport models [Gauss *et al*., 2006]. The obtained results allowed determining that the resulting radiative forcing is strongly dependent on the location and altitude of the modelled ozone change and varies between 0.25 W $m^{-2}$ and 0.45 W $m^{-2}$ due to ozone change in the troposphere and −0.123 W $m^{-2}$ and +0.066 W $m^{-2}$ due to the stratospheric ozone change.

In Dentener *et al*. [2006] the tropospheric composition change to be expected in the near future (year 2030) is investigated using 26 state-of-the-art global atmospheric chemistry transport models and three different emissions scenarios. Based on the ensemble mean model results, by 2030 global surface ozone is calculated to increase globally by $4.3 \pm 2.2$ ppb for the IPCC SRES A2 scenario [Nakicenovic *et al*., 2000]. This study shows the importance of enforcing current worldwide air quality legislation and the major benefits of going further. Nonattainment of these air quality policy objectives, such as expressed by the IPCC SRES A2 scenario, would further degrade the global atmospheric environment.

The analysis of the climate change impacts on air quality and its feedback mechanism is nowadays a well recognised approach at the global scale. Nonetheless, studies from the regional to a country scale are not so widespread. The highest number of studies can be found for USA [e.g. Hogrefe *et al*., 2005]. Over Europe some studies have addressed this issue [*e.g*. Szopa *et al*., 2006] pointing that by 2030 estimated ozone levels, in July, may increase up to 5 ppb. In Europe and at country level these studies are still reduced and only applied for episodic situations [e.g. Borrego *et al*., 2000]. Additionally, the interaction between climate change, forest fire emissions and air quality is still poorly discussed. In this scope, the main objective of this thesis is to investigate the role of climate change in forest fire activity and its impacts on air quality patterns over Portugal through the projection of future area burned and pollutants emissions under the IPCC SRES A2 climatic scenario.

The importance of the regional weather patterns in the forest fire dynamics is the first main aim to be attained. In Chapter 2 a synoptical analysis is conducted in order to assess the temporal/spatial evolution of the weather patterns most related to forest fires in Central Portugal. Worldwide several studies have already discussed the relationship between the atmospheric field patterns and the forest fire activity [*e.g.* Skinner *et al*., 1999]. In Portugal this has been addressed by several authors using different approaches [*e.g.* Lourenço, 1988]. In Chapter 2 the temporal evolution of different atmospheric variables and the area burned in Central Portugal is assessed between 1980 and 2001. This analysis allows determining the pre-event situation as well as the pos-event atmospheric conditions namely in what concerns temperature, wind and humidity. The Iberian thermal low is an important weather type in the Iberian summer climatology [Hoinka and Castro, 2003]. So, the link between the occurrence of Iberian thermal lows and large forest fires is also investigated. The work presented in Chapter 2 was developed under the Portuguese-German Concerted Action and was submitted to the *International Journal of Wildland Fire* [Hoinka *et al*., 2007a].

Chapter 2 identifies the most relevant regional scale atmospheric field patterns to forest fire events. In addition, in Chapter 3 the role of the surface meteorological conditions that lead the forest fire statistics in Portugal is assessed and discussed. Previous studies already settled the weather as a crucial variable in the development and supporting of forest fires in southern Europe namely in Portugal [*e.g.* Viegas *et al*., 1992]. An adequate way to study this relationship is through the estimation and analysis of the fire weather index components over Portugal. A fire weather rating system represents a way to rank the level of risk of a region to forest fires ignition and propagation. Since 1998, the Canadian Fire Weather Index (FWI) System [Van Wagner, 1987] is used by the Portuguese authorities to assess the level of risk during the summer months namely between May and October. In Chapter 3 the relationship between the weather, the FWI components and the area burned and the number of fires is established for the period between 1980 and 2004 for 12 districts over Portugal. It was not possible to analyse the 18 Portuguese districts due to meteorological data limitations. The weather and the FWI components were used as predictors for the area burned and the number of fires for the studied period. The year 2005 was used to validate the obtained statistical models. Additionally, the most significant variables that explain the forest fire activity in Portugal were discussed. The work presented in Chapter 3 was published in the *International Journal of Wildland Fire* [Carvalho *et al*., 2007a].

Chapters 2 and 3 analyse and discuss the role of the atmospheric conditions in the development and enhancement of the forest fire activity over Portugal. The obtained results give supporting information that can be used to assess the impacts of climate change on fire weather risk and on fire activity over Portugal. In this scope, Chapter 4 investigates the potential impacts of climate change on fire weather. The analysis was based on the assessment of two climatic scenarios: the reference scenario (1961-1990) and the IPCC SRES A2 scenario (2071-2100) [Nakicenovic *et al*., 2000]. For the analysed time slices the IPCC SRES A2 is consistent to a 2 x $CO_2$ climatic scenario. The impact assessment study was based on the outputs of the regional climate model HIRHAM [Christensen *et al*., 1996] at two high spatial resolutions, 12 km and 25 km. The impact of different spatial resolutions on fire weather risk projections was also assessed. The obtained projections allowed determining the most affected Portuguese districts in terms of fire weather and also the temporal and spatial characteristics of the projected impacts. Part of the work presented in Chapter 4 was presented in Carvalho *et al*. [2006a].

Based on the relationships between the weather, the fire weather risk and the fire activity in Portugal developed in Chapter 3 and on the fire weather risk projections discussed in Chapter 4 it was possible to investigate the area burned and the number of fires in Portugal by the end of the 21st century. Hence, Chapter 5 presents the projected increases on the annual area burned and on the annual number of fires for the 12 Portuguese districts. The monthly distribution of the area burned and the number of fires is also assessed. The work developed in Chapters 4 and 5 has been submitted to the *Climatic Change* journal [Carvalho *et al*., 2007b].

One of the main goals of this thesis is to study the role of future forest fire activity on air quality over Portugal. The area burned projections estimated in Chapter 5 allow determining the future forest fire emissions based on emission factors, burning efficiency and fuel load characteristics typical of the Portuguese ecosystems. To evaluate the impact of climate change and future forest fire emissions on pollutants concentration in the atmosphere the application of an air quality numerical system is fundamental. The MM5/CHIMERE [Grell *et al*., 1994; Schmidt *et al.*, 2001] modelling system was applied over two domains, Europe and Portugal, at two spatial resolutions, 50 km and 10 km, respectively. Monthly and hourly averages of ozone and particulate matter were investigated from May 1st to October 30th for 1990 and 2100 climates. A detailed analysis was conducted in order to investigate the impacts of climate change and future forest fire emissions on pollutants concentrations in the atmosphere. The work discussed in Chapter 6 was presented at two conferences [Carvalho *et al*., 2007c,d].

Finally, in Chapter 7 a brief summary of the main results is carried out. Additionally, the general conclusions are explored and possible future developments discussed.

# 2. Regional scale weather patterns and fire activity in Portugal

## 2.1. Introduction

Diverse scales of atmospheric motion influence wildfire's behaviour, from the large-scale weather patterns (~ 1000 km) down to the local fire-generated flow of a few tens of meters. Several studies have correlated large-scale, synoptic-scale and local-scale weather to wildfire activity. Most of the studies that analyse the potential relationship between the atmospheric weather patterns and the forest fire activity have as main objective the development of forecast models that support the fire management agencies well in advance of the fire season, e.g. seasonal fire forecast [Westerling *et al.*, 2003].

In 1969, Schroeder constructed the fire weather climatology for the United States through the linking of large-scale synoptic patterns with regional to local scale fire danger. Brotak and Reifsnyder [1977] showed that 80 % of major fires in the eastern United States occurred associated to frontal passages which were associated with a trough at 500 hPa. In California, the large-scale atmospheric circulation patterns intensified by local wind patterns revealed an important role in the severe 2003 fire season [Westerling *et al.*, 2004]. Crimmins [2006] related the daily surface fire weather index values to their respective synoptic circulation patterns across the southwest United States. Three key circulation patterns representing broad southwesterly flow and large geopotential height gradients are associated with over 80 % of the extreme fire weather days identified. For Canada, statistically significant positive correlations were established between regional area burned and the 500 hPa pressure field anomaly series [Skinner *et al*., 1999; 2002]. Johnson and Wowchuk [1993] concluded that the large wildfires in the southern Canadian Rocky Mountains showed significantly lower fuel moisture conditions and many mid-tropospheric surface-blocking events (high-pressure upper level ridges) during July and August.

Over the Iberian Peninsula (IP) some studies have already analysed the synoptic conditions associated to the occurrence of large wildfires [Lourenço, 1988; Ramos and Ventura, 1992; Alcoforado and Almeida, 1993; Millán *et al*., 1998; Pereira *et al*., 2005; Trigo *et al*., 2006; Viegas *et al*., 2006]. In 1988, Lourenço examined the synoptic conditions that characterized eight major forest fires that occurred in 1986 in Central Portugal. The author found that in seven out of eight of the fires, the synoptic conditions were the same: an extension of the Azores High Pressure System to the centre of Europe, which brought warm, dry easterly winds. Fires began under easterly winds and ended after the winds shifted to westerlies, which brought moist, cool maritime air. Ramos and Ventura (1992) classified in six categories the synoptic conditions prevailing in the four months of the fire season (June–September) in Portugal between 1987 and 1989. The two synoptic conditions in which fire risk was found to be extreme were the extended Azores High Pressure System (maximum temperature of 31.2 ºC and easterly winds from the Iberian Peninsula) and the elongated Thermal Low Pressure System from the Sahara (maximum temperature of 32.5 ºC and an advection of warm, dry air from North Africa). These two synoptic situations were found to be the most favourable for the development of forest fires, where the maximum temperature were the highest, the relative humidity the lowest and the winds had an easterly continental component.

Pereira *et al.* [2005] discussed the synoptic conditions associated with large wildfires in Portugal and investigated the link between the precipitation, the meteorological fire index based on the geopotential height at 500 hPa level and the area burned during summer. The authors concluded that the occurrence of large wildfires is related to a typical atmospheric circulation pattern dominated by a strong ridge located over the Iberian Peninsula. More recently, Trigo *et al*. [2006] analysed the atmospheric conditions related to the devastating 2003 fire season in Portugal. Synoptic conditions associated with wildfire occurrences were characterised by the temperature field at 850 hPa. At surface, maximum and minimum temperatures, relative humidity, and wind speed and direction, recorded at synoptic stations were also assessed. The authors concluded that the observed anomalies of daily values of temperature at 850 hPa surpassed historical maxima over southern and central Portugal on the 1st and 2nd of August, respectively. Additionally, the days with the highest amounts of daily area burned were characterised by large anomalies of surface meteorological variables that favour wildfire activity, namely surface maximum and minimum temperature, relative humidity, and wind speed and direction.

During the summer months over the IP the dominant weather type is a thermal low [Hoinka and Castro, 2003]. A thermal low is a warm, shallow, non-frontal depression which forms above continental regions, mostly in the subtropics but also in the midlatitudes [Alonso *et al*., 1994]. These systems form mostly during summer months because of the intense surface heating over land. Thermal low surface conditions are characterized by dry and hot weather which are favourable for wildfires starting and spreading. Hoinka and Castro [2003] analysed the ReAnalysis Project (ERA) data provided by the European Center for Medium-Range Weather Forecast (ECMWF) between 1979 and 1993. A criterion was applied in order to detect the thermal low signal over the IP. During the peak months of July and August, thermal lows were observed in 45 % of the days. The pre-peak season (May and June) showed a higher frequency of occurrence (14 % and 34 %) than the pos-peak months of September and October (18 % and 2 %).

The way the thermal low weather pattern interacts with the forest fire activity is still a point of debate. The potential relationship between both phenomena is discussed in this chapter. The relationship between the atmospheric characteristics and the area burned in Portugal is also analysed through lagged covariance. The statistically relevant evolution of the atmospheric fields associated with wildfires in Portugal is also presented. In particular, it allows determining the pre-event situation as well as the pos-event conditions. This chapter discusses the temporal/spatial evolution of the weather patterns most related to forest fires in Portugal.

## 2.2. Data and Methods

Three data series were used in this study: the ERA40 Reanalysis series provided by the ECMWF and a time series of fire activity as provided by the Portuguese General Directorate of Forestry Resources (DGRF). The third series contains Iberian daily thermal low's occurrence based on ERA40 taken from Hoinka *et al*. [2007b]. Hence, firstly the forest fire data used in this study are described - *Forest fire activity in Central Portugal*. Secondly, the Iberian Peninsula summer climate and the thermal low characteristics are analysed - *The ERA40 data and the summer climate of the Iberian Peninsula*.

### 2.2.1. Forest fire activity in Central Portugal

The fire activity database consists of daily information on the number of fires and area burned by district for the period between 1980 and 2001. Annual area burned of more than 8000 ha is observed in the districts of Central Portugal: Castelo Branco, Coimbra, Guarda, and Viseu (Figure 2.1). All abovementioned districts have the highest area burned among all 18 Portuguese districts.

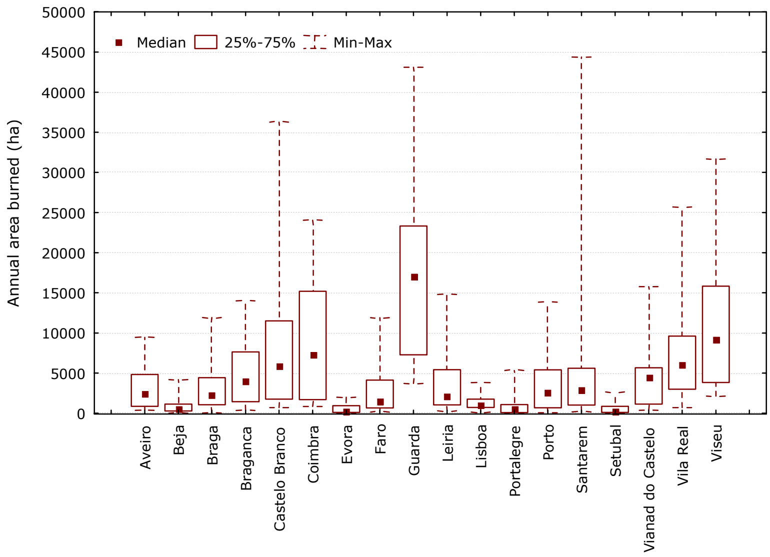



Figure 2.1 - Annual area burned (ha) by Portuguese district from 1980 to 2001.

Therefore the analysis was concentrated in the Central region of Portugal, the belt between Spain and the coast, meridionally roughly limited by the rivers Douro and Tejo. The Aveiro district was added to the abovementioned four districts to form a zone belt (Figure 2.2).

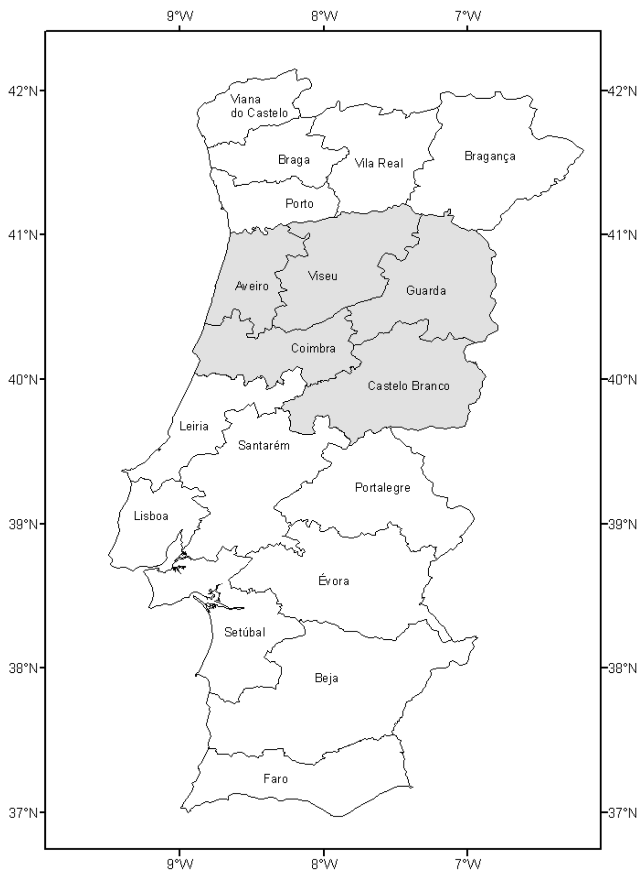



Figure 2.2 – Map of Portugal with the districts identification. The districts used in this analysis are shaded.

The peak season of wildfires is the period between June and September (JJAS) (Figure 2.3). Pereira *et al*. [2005] also pointed out that 93 % of the annual area burned was registered during these months. Thus the analysis was restricted to this season because the chosen districts and period cover a great part of Portuguese wildfire activity. To get a sufficient strong signal, only days with area burned exceeding 500 ha were considered in the correlation analysis. Apparently, this is an arbitrary limit; however, it allows suppressing small and ineffective fires, probably also days with unfavourable wildfire conditions.

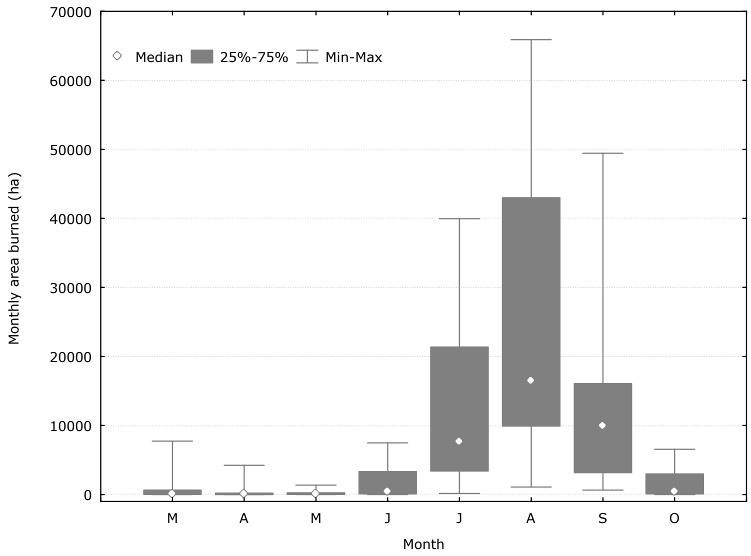



Figure 2.3 – Monthly area burned (ha) (from March to October) for the districts of Aveiro, Viseu, Coimbra, Castelo Branco, and Guarda from 1980 to 2001.

The area burned was used in this analysis because significant statistical relationships were established between the area burned and the weather variables [Viegas *et al.*, 1992; Viegas and Viegas, 1994]. These relationships will be explored in Chapter 3.

### 2.2.2. The ERA40 data and the summer climate of the Iberian Peninsula

The atmospheric data used are part of the ERA40 set covering the period 1958-2001 generated by the ECMWF Reanalysis Project [Uppala *et al.*, 2005]. The wind, geopotential height, pressure, temperature and humidity data are available at a 1º x 1º horizontal grid resolution. In the vertical, pressure level data at 1000, 925, 850, 775 and 500 hPa as well as model level data for approximately 10, 100, 500 and 1000 m above ground level (agl) were used. All fields are available four times a day, but daily mean fields were also considered.

The particular conditions dominating the fire activity are short-term meteorological extremes that are not strongly related to monthly or seasonal climate variations. Nevertheless, the climatic state of the extended summer period (JJAS) is briefly presented showing summertime features which provide in general favourable conditions for wildfires. Figure 2.4 shows the daily averages of temperature, specific humidity and wind speed at 10 m and the mean sea level pressure (mslp), based on the ERA40 dataset.

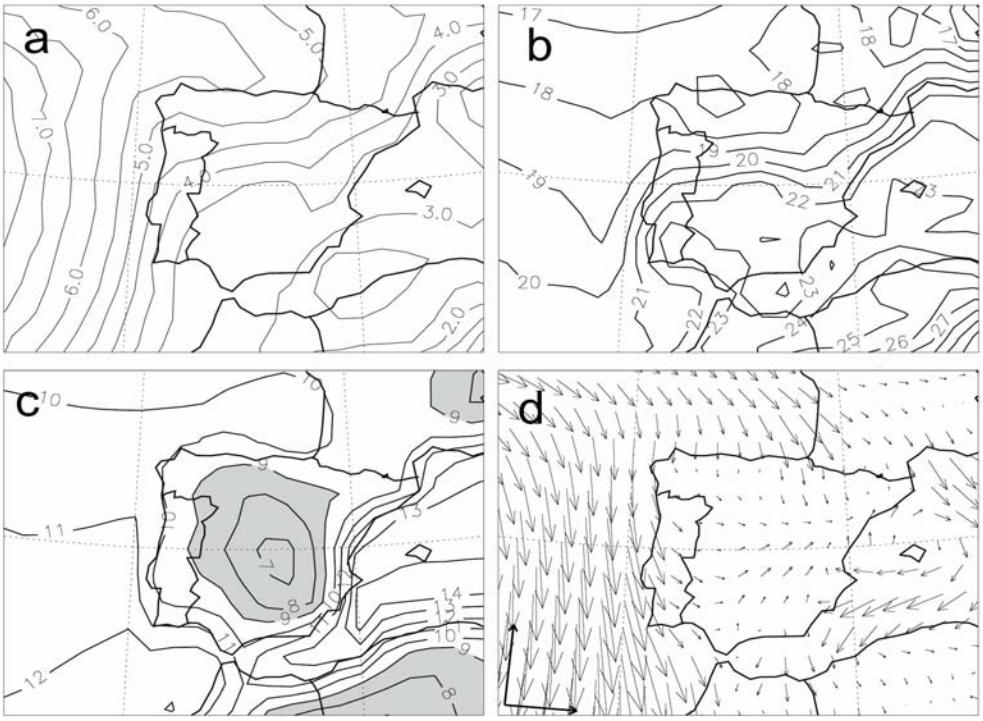


Figure 2.4 – Daily averages of surface parameters at 10 m agl for JJAS from 1980 to 2001 from ERA40: a) mslp (increment of 0.5 hPa; reduced by 1013 hPa); b) temperature (ºC); c) specific humidity; and d) wind speed (wind vector at lower left indicates 5 m $s^{-1}$). The shaded area in (c) indicates areas with humidity lower than 9 g $kg^{-1}$ in order to emphasize the Central Iberian minimum.

Because the thermal low's peak time is at 18 UTC (at this time occurs the daily minimum surface pressure) [Hoinka and Castro, 2003], it appears only weakly in the daily averaged mslp pattern (a) in the southern part of the IP. The averaged temperature (b) rises up to 23ºC above the IP. In turn the specific humidity (c) decreases to less than 7 g $kg^{-1}$. The wind field (d) shows in general a northerly flow above the Atlantic Ocean which turns to north-westerlies above Portugal due to the strong surface pressure gradients (not shown). Above Spain this flow turns to southerly directions with weak wind speeds of around 1 m $s^{-1}$.

As already pointed out the thermal low is the dominant weather type during the summer months over the IP. The thermal low's center is usually found above the IP's center, hence remarkable surface pressure gradients occur at the periphery of the low which coincide roughly with the peninsula's coastal boundaries [Hoinka and Castro, 2003]. This surface pressure pattern is used to obtain a temporal series of a parameter characteristic for Iberian thermal lows. Hoinka and Castro [2003] give a detailed description of the criteria applied to obtain the Iberian thermal low days. A brief description of the applied criteria is described here.

To decide if there is a heat low above the IP, the mean sea level pressure (mslp) at 06 and 18 UTC and the structure of the 925 hPa surface are considered. Data from the 925 hPa level are preferably used because the IP's mean surface height is at about the same level. Following Hoinka and Castro [2003], at the peak time of the heat low (18 UTC), height differences ($z^*$) in the 925 hPa surface between locations in peripheral and interior regions of the IP are determined along the coastal boundaries of the IP (criterion (v) in Hoinka and Castro [2003]). Additionally, the minimum height of the 925 hPa surface must be located above the IP (criterion (iii)). The averaged differences ($z^*$) form the considered time series. The averaged height difference at 18 UTC ($z_{18}^*$) is most prominent for the thermal low's occurrence because at this time occurs the daily minimum surface pressure in the IP's center.

The series with Iberian thermal low occurrence were taken from Hoinka *et al*. [2007b] containing objectively determined occurrence of the Iberian thermal low based on ERA40 data. Figure 2.5 shows that in summer more than 50 % of all days are thermal low events.

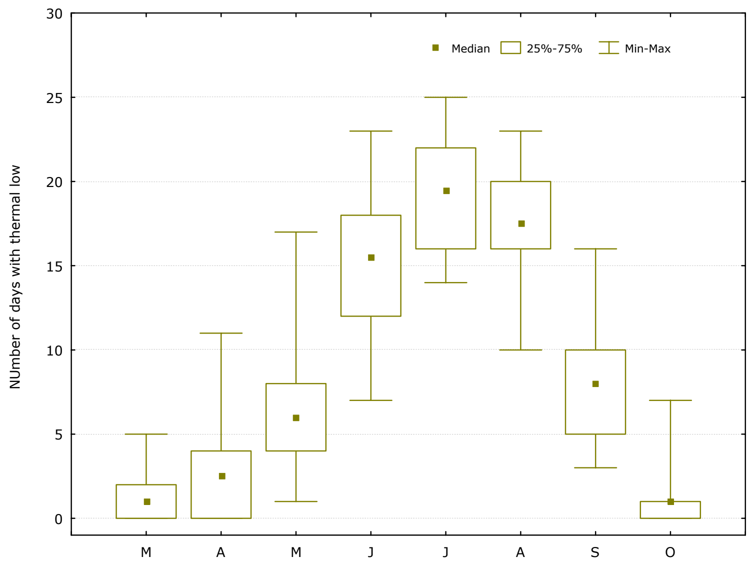



Figure 2.5 - Number of days with thermal low, from March to October, between 1980 and 2001, by month.

It is a standard method in meteorology to calculate covariance and correlations of meteorological fields with parameters or with single station time series [von Storch and Zwiers, 1999]. The lagged correlations of atmospheric parameter fields, such as temperature, humidity and wind with daily area burned in Portugal were determined.

The calculations describe the statistically relevant evolution of atmospheric fields associated with wildfires. In particular, it allows determining the pre-event situation as well as the development after the fire's outbreak.

The ERA40 analysis, thermal low and area burned data series, are used in order to determine statistics for the period between 1980 and 2001 by applying the lagged covariance method. The period was chosen according to the limits of all data series. The evaluated statistics consist of covariance of area burned (AB) in Portugal and grid point values of variables from the ERA40. Let $C(b,c|\tau)$ denote the covariance of a variable c where b leads c with lag $\tau$. For instance, all covariance $C(AB,\vec{v}\,|\tau)$ of the area burned AB(t) series with the components of the horizontal velocities vector $\vec{v}\,(x,y,z,t)$ will be used to determine the statistical flow feature associated with strong wildfires. Additionally, statistical features for humidity, temperature, geopotential height and pressure are determined.

In Portugal, the wildfire events have duration of a few days only. Correspondingly, the area burned autocorrelation decays quickly after lag zero (Figure 2.6). The lags are restricted to the interval $|\tau| \leq 5$ days because the majority of wildfires are short-lived and covariance are small for $\tau$ beyond 5 days. Figure 2.6 presents the autocorrelation functions considering all fires, only area burned above 500 ha, and only area burned above 1000 ha.

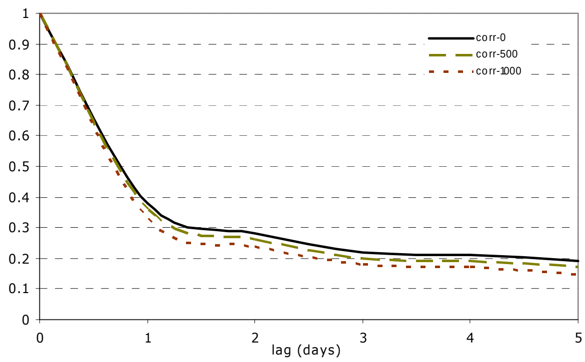



Figure 2.6 - Autocorrelation function for daily area burned $C(AB,AB|\tau)$ concerning all data (corr-0), area burned above 500 ha (corr-500) and area burned above 1000 ha (corr-1000).

To simplify the results, the covariance fields are normalized by the standard deviation of the daily area burned (1105 ha) computed from June to September between 1980 and 2001 allowing the resulting fields to be interpreted in units of the correlated meteorological parameters of ERA40.

## 2.3. Results and Discussion

In this section the obtained results concerning the cross-covariance between the area burned in Central Portugal and the weather patterns between 1980 and 2001 are presented – *Lagged covariance analysis*. The thermal low relationship to the area burned in Central Portugal is also discussed – *Fire activity and thermal low*.

### 2.3.1. Lagged covariance analysis

In the following the time series of area burned is correlated with pressure, geopotential height, temperature, humidity, and wind from the ERA40 data.

*Pressure and geopotential height*

Pereira *et al*. [2005] determined composite fields of the geopotential height of the 500 hPa and the 850 hPa surfaces. These composite fields consisted of days of highest values of area burned in Portugal. At 500 hPa a weak ridge of high pressure was determined above the IP associated with an anomaly north of the IP. Other studies [*e.g*. Skinner *et al*., 2002] have already established significant correlation between the 500 hPa surface and the area burned in Canada.

Based on the lagged covariance method the development of the pressure anomaly can be studied for different lag times. Figure 2.7 exhibits the evolution of the covariance field $C(AB,z500|\tau)$ for the geopotential height of the 500 hPa surface (z500). As stated before, only days with area burned exceeding 500 ha are considered in the correlation.

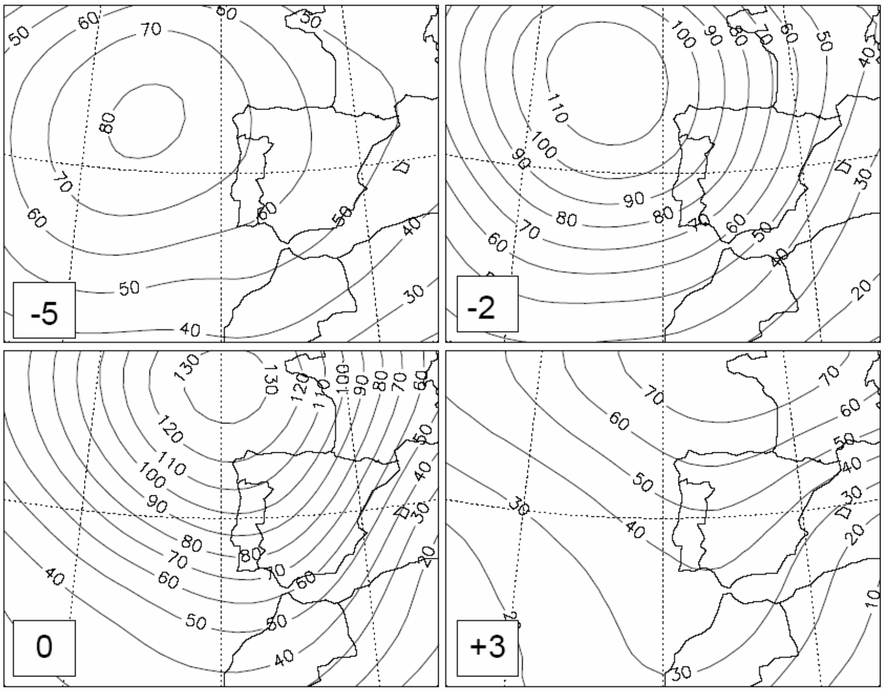



Figure 2.7 – Cross-covariance C(AB,z500|τ) (m) of the normalized area burned (AB) in Central Portugal with the height of the 500 hPa surface (z500). The time lag is indicated in each panel.

A positive covariance anomaly appears to the west of the IP at τ=-5 days and moves then toward Brittany in France where it arrives at τ=0. The amplitude of the anomaly is stronger in advance of the event, reaching more than 80 m (τ=-5), than after the event when it decreases more rapidly toward 50 m at τ=+5 (not shown). The maximum anomaly occurs at lag equal 0 with more than 130 m. Applying a time series of area burned where all wildfires are considered, the evolution is comparable but the maximum reaches only 25 m at τ=0. On the other hand for a time series where no fires are accepted except those days when the area burned exceeds 1000 ha, the peak anomaly reaches more than 200 m. This indicates that the correlation is stronger for the days with larger area burned.

The mean sea level pressure field also shows a positive covariance anomaly over the Atlantic Ocean (Figure 2.8).

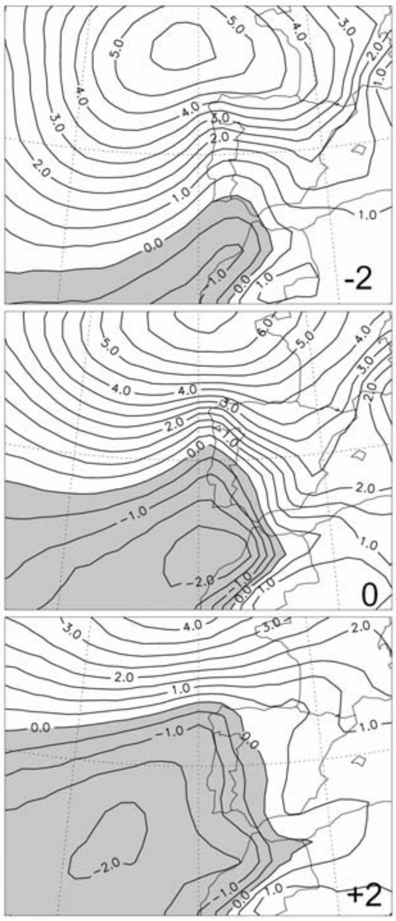



Figure 2.8 – Cross-covariance C(AB,mslp|τ) (hPa) of the normalized area burned in Central Portugal with the mean sea level pressure (mslp). The time lag is indicated. Negative covariance is shaded.

Comparing Figure 2.7 and Figure 2.8 it is interesting to note an increase with height in the positive covariance anomaly. At the surface the pressure maximum anomaly results to 6.7 hPa whereas at 500 hPa this increases to 9.2 hPa which is equivalent to the maximum height of 135 m. With increasing lag time a negative cross-covariance anomaly develops stretching from the southern Atlantic toward the southwestern edge of the IP. This negative anomaly reaches its maximum between $\tau=1$ and $\tau=2$ and then it falls back toward the Atlantic Ocean. The isolines of pressure are squeezed between the northerly positive and the southerly negative covariance anomaly over the western IP coast, particularly over northern Portugal and Galicia, Spain. This leads to an enhanced ageostrophic flow that may represent an important feature for forest fires spreading.

*Temperature and humidity*

Figure 2.9 shows the covariance field C(AB,T|τ) of the area burned with the mean daily 10 m temperature. Viegas *et al*. [2006] pointed that large wildfires events are preceded by several days with meteorological conditions of enhanced fire weather risk. This is clearly reflected in the covariance fields of temperature and specific humidity. At lag=-5 days there is already a strong signal of high temperature of up to 4 K. This increases further up to 7 K at τ=0 and decreases rapidly after the event. The comparison of τ=-5 with τ=+5 fields shows that in advance of the event a strong temperature configuration is apparent. At τ=0 the temperature anomaly is concentrated on locations in Central Portugal and the Spanish Extremadura region. Considering the 18 UTC fields, instead of the daily averages, the peak value at τ=0 increases up to 8 K (not shown). However, the general pattern remains the same.

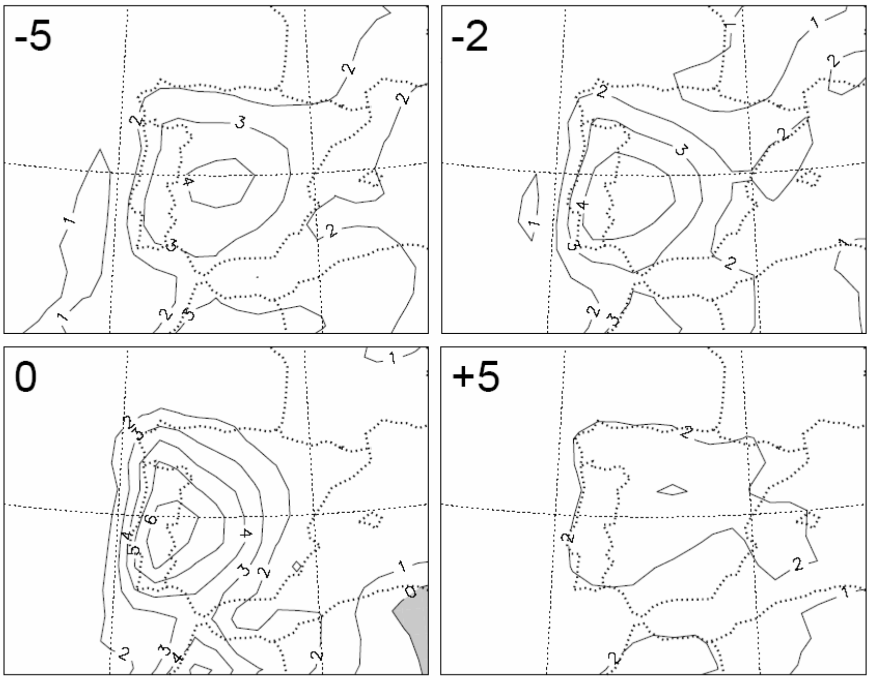



Figure 2.9 – Cross-covariance C(AB,T|τ) (K) of the normalized area burned in Central Portugal with the daily mean temperature (T). The time lag is indicated.

The surface humidity and the humidity content of the overlying air are key parameters for wildfires [Viegas *et al*., 1992]. Figure 2.10 shows the covariance field C(AB,q|τ) of the area burned with the atmospheric specific humidity (q) at 18 UTC. The peak negative covariance anomaly appears already one day before the event. This indicates that before the event the humidity is very low. After $\tau$=0 the anomaly disappears rapidly.

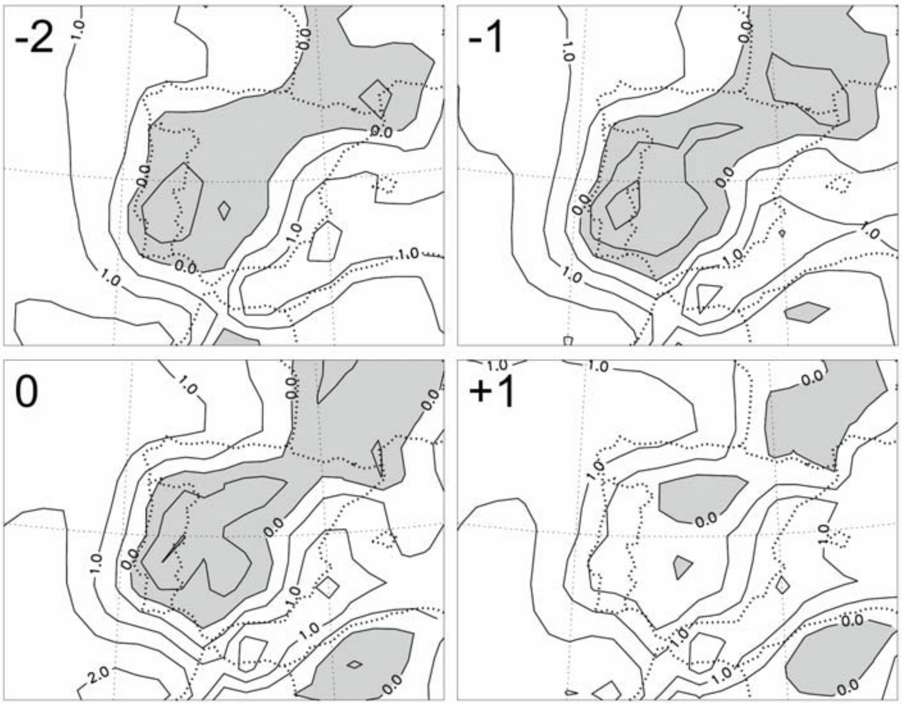



Figure 2.10 - Cross-covariance C(AB,q|$\tau$) (g kg$^{-1}$) of the normalized area burned in Central Portugal with the specific humidity (q) at 18 UTC. The time lag is indicated. Units in g kg$^{-1}$; increment of isolines is 0.5 g kg$^{-1}$; Negative covariance are shaded.

*Wind*

In Figure 2.11 the wind is given at 10 m agl, 1000 m agl and at 850 hPa for various lags. At 10 m the wind apparently follows the coastline at the western and southern edge of the peninsula. The ageostrophic wind exists due to the strong surface pressure gradients as apparent in Figure 2.8. Above Portugal at $\tau$=-2 the flow comes from the north. At $\tau$=0 the wind turns to northeast and southeasterlies and at $\tau$=+2 the southeasterly flow dominates. This feature becomes much more evident at 1000 m agl with an easterly flow at $\tau$=0 and southeasterlies at $\tau$=+2. This pattern strengthens at the 850 hPa surface and the effect of flowing-around the IP is weakly visible at $\tau$=+2. At lower levels this flow-around effect is much more evident where particularly the eastern and southern edge of the peninsula seems to 'force' the flow.

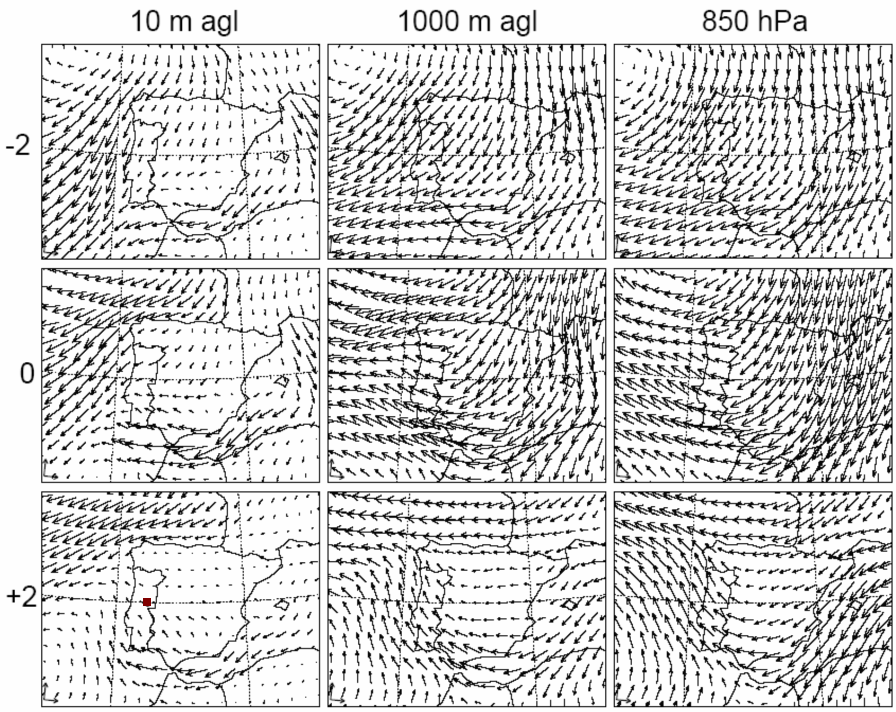
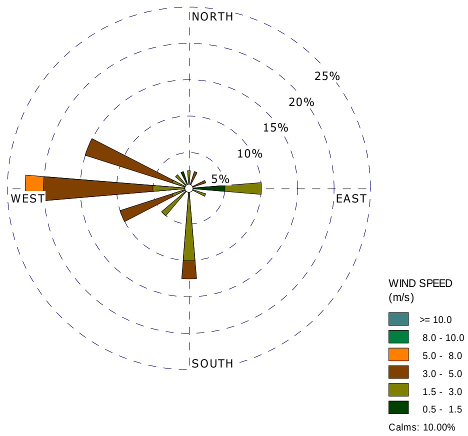


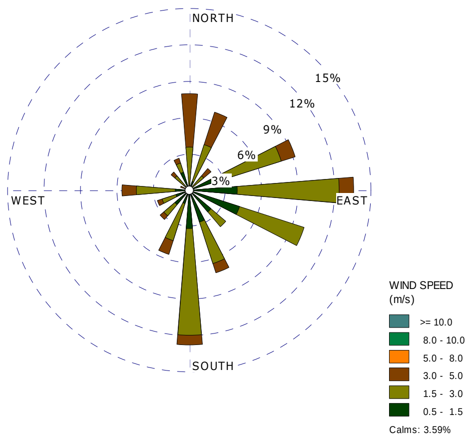

Figure 2.11 - Cross-covariance C(AB, $\vec{v}$ |τ) (m s$^{-1}$) of the normalized area burned in Central Portugal with the wind at 10 m agl, 1000 agl and at the 850 hPa surface pressure. The time lag is indicated. The arrows in the lower left corner indicate 2.5 m s$^{-1}$.

The calculations indicate the most probable statistical wind structure during the occurrence of large forest fires in Portugal, also confirming the experience of fire-fighters that report East wind dominance when large forest fires occur.

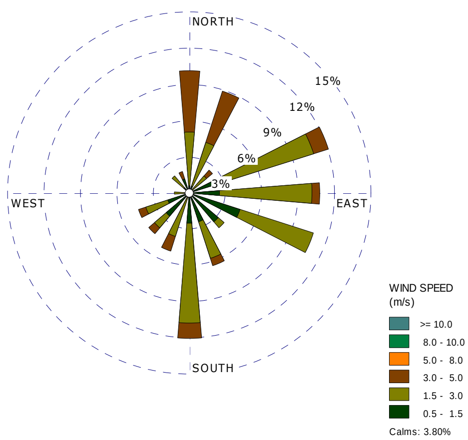
A final corrobation of the covariance fields of wind (Figure 2.11) comes from surface wind measurements taken at Castelo Branco between 1985 and 1995, at 12 UTC (Figure 2.12). The figure shows wind direction frequencies summarized over sectors of 22.5º. The location of Castelo Branco is marked by a red spot in the lower left hand panel of Figure 2.11. For days without wildfires (a) about 50 % of the wind comes predominantly from the westerly sector (SW-NW). Apparently, the situation is quite different during wildfires (b,c). The most prominent sectors where the wind comes from are the eastern and the southern, both with a frequency of 13-14 %.




a)




b)




c)

Figure 2.12 – Wind rose for Castelo Branco between 1985 and 1995 at 12 UTC, from June to September for a) days with no fire, b) days with area burned higher 500 ha and c) days with area burned higher than 1000 ha.

### 2.3.2. Fire activity and thermal low

Thermal lows are classified as one of the important weather types in the Iberian summer climatology [Hoinka *et al.*, 2007b]. Besides the extended Azores ridge of high pressure, Ramos and Ventura [1992] identified an elongated thermal low pressure extending from the Sahara as a synoptic pattern in which fire risk was found to be extreme. The occurrence of an Iberian thermal low is strongly related to its Saharian counterpart.

A correlation based on monthly averaged area burned and monthly number of Iberian thermal low days shows that the area burned is highly correlated to the number of thermal low days as well as to the average monthly $z_{18}^*$ and maximum $z_{18}^*$. At a 95% confidence interval, statistical significant Spearman correlations were obtained between the monthly area burned and mean monthly $z_{18}^*$ (r=0.49) and the monthly number of thermal low days (r=0.57). The obtained correlations are positive and significant indicating that a relationship exists between thermal low conditions and fire activity in Portugal.

Table 2.1 shows wildfire statistics with those of thermal lows [from Hoinka *et al.*, 2007b] for all summers (JJAS) between 1980 and 2001.

Table 2.1 – Fire activity statistics for Central Portugal and Iberian thermal lows, from June to September, between 1980 and 2001.

| **Data** | | **Sample days** | **Fire events (%)** | **Mean area burned (ha)** | **σ (ha)** | **$Z_{18}^*$ (m)** |
|---|---|---|---|---|---|---|
| full period | | 2684 | 100 | 392 | 1105 | 7.5 |
| | AB≠0 | 2404 | 99.9 | 438 | 1159 | 7.8 |
| | AB≥500 | 449 | 37.8 | 1949 | 2083 | 8.1 |
| thermal low | | 1328 | 52.8 | 392 | 956 | 10.5 |
| | AB≠0 | 1249 | 52.8 | 417 | 982 | 10.5 |
| | AB≥500 | 239 | 19.3 | 1767 | 1653 | 10.4 |
| no thermal low | | 1356 | 47.2 | 393 | 1233 | 4.6 |
| | AB≠0 | 1155 | 47.1 | 461 | 1325 | 4.9 |
| | AB≥500 | 210 | 18.5 | 2155 | 2470 | 5.6 |

The entire period consists of 2684 days, which includes 1328 days with a thermal low over the IP. For the chosen period, the averaged area burned is 392 ha (σ=1105 ha), the same amount results for thermal low days (σ=956 ha) and 393 ha (σ=1233 ha) for days without a thermal low. This weak difference can be explained by the fact that the usual summertime day condition is close to thermal low conditions. Table 2.1 presents, for the entire data sample, a weak increase of $z_{18}^*$ with increasing area burned. On the other hand, the differences on the $z_{18}^*$ between days with and without thermal low are strong: 10.4 m *vs.* 5.6 m for area burned greater than 500 ha. But in contrary, the averaged area burned is lower (1767 ha) for the thermal low days sample than for the non-thermal low days one (2155 ha). A further statistical feature is given in Figure 2.13. It shows the cross-covariance function between the area burned and the occurrence of thermal low ($z_{18}^*$) indicating that the peak amount of area burned happens up to three days after the appearance of an Iberian thermal low. This lagging suggests that a comparison of averaged values on Table 2.1 could not show significant differences between both events. The lagging also suggests that the existing surface easterly flow in advance of wildfires might transport heated and dry air from the Iberian Peninsula's center towards Central Portugal, supporting favourable wildfire conditions in this region.

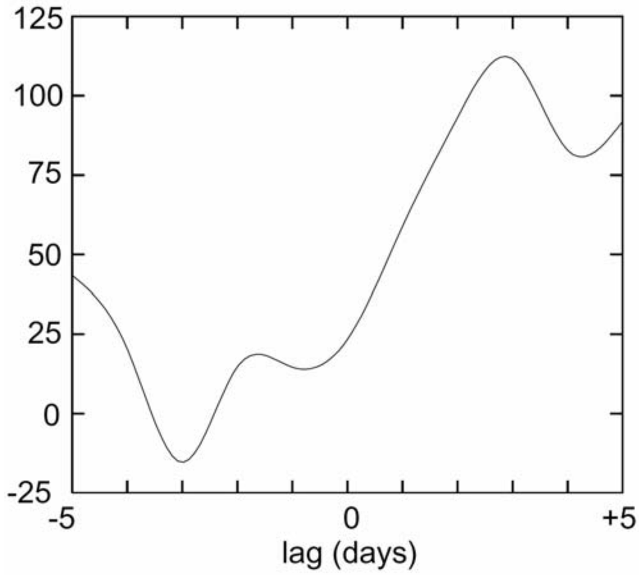
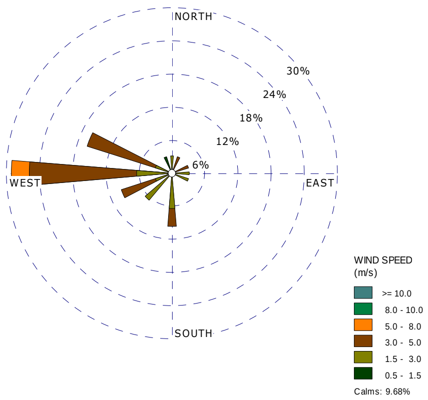
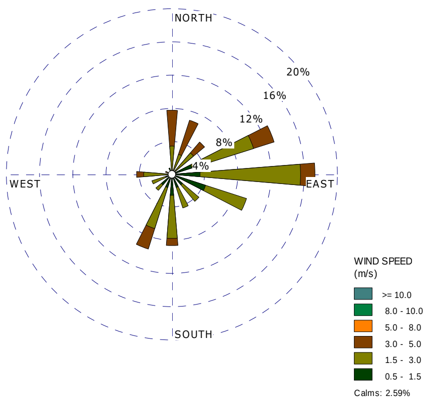



Figure 2.13 - Cross-covariance C(AB, $z_{18}^*|\tau$) (hPa) as a function of time lag.

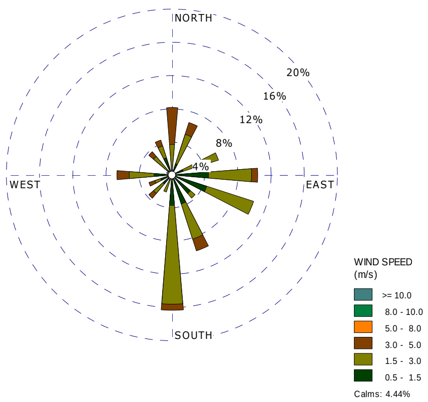
Figure 2.14 presents the wind rose for Castelo Branco for days with and without thermal low. As can be seen for the days with no heated low and no forest fires (a) the main flow is from west. On the other hand, for the days with area burned above 500 ha and no heated low (b) the easterly flow is dominant. For the days with heated low and area burned over 500 ha (c) the highest wind frequency comes from south.




a)




b)




c)

Figure 2.14 - Wind rose for Castelo Branco at 12 UTC between 1985 and 1995, from June to September for a) days with no fire and no heated low, b) days with area burned higher 500 ha and no heated low and c) days with area burned higher than 500 ha and heated low.

In a changing climate and according to Hoinka *et al*. [2007b] the Iberian thermal lows tend to strength by decreasing the central Iberian surface pressure from 1012.2 to 1010.5 hPa and increasing its variability by about 7 % in magnitude. Additionally, it is also projected an increase of about 60 % in the number of thermal low days.

The increase in the frequency of thermal low days is closely connected to an increase on the dry spells duration what may deeply impact fire weather risk over the Iberian Peninsula especially over Portugal.

## 2.4. Summary and conclusions

Atmospheric conditions determine the spread of a fire and in turn the extension of area burned. In this chapter regional scale atmospheric fields were correlated to summertime wildfire in Central Portugal. In order to study this relationship, the typical structural evolution of the atmospheric field patterns in a wildfire event was investigated by lagged covariance. The daily area burned in Central Portugal was chosen as the parameter to be correlated with atmospheric fields provided by the ERA40 data. The used time series consists of daily area burned higher than 500 ha. Lagged covariance was determined for the period 1980 to 2001.

It is know that during summer in the lower troposphere, the thermal low is the dominant atmospheric pattern over the Iberian Peninsula. This surface-based depression is notable up to 925 hPa. The mean summertime conditions of temperature and humidity are favourable for the ignition and spreading of wildfires. In this sense, a monthly correlation analysis was performed in order to assess the influence of the number of days with thermal low in the monthly area burned.

The analysis of the lagged covariance revealed that five days in advance of a fire event a strong positive anomaly exists in the surface pressure field at 500 hPa appearing to the west of the Iberian Peninsula. In advance of fire events the flow in the lowest 1000 m above ground comes from the north, turning to easterlies at lag time zero and finally coming from the southeast during the post-event phase. Surface wind statistics taken at Castelo Branco support these results. Up to five days in advance of the event, the temperature shows high values above Central Portugal and the Spanish Extremadura region. The temperature reaches its maximum at lag zero and decreases rapidly after the event. A similar behaviour is shown by the specific humidity near the surface with low magnitudes in advance, minimum at lag zero and rapid increase after the event.

The statistics of Iberian thermal lows indicate a frequency of about 50 % during summertime. Cross-covariance regression between Iberian thermal low and area burned showed that the peak amount of area burned occurs up to three days after the appearance of a thermal low. This suggests that in the pre-phase of a wildfire heated air is transported from the peninsula’s centre toward Portugal. The monthly analysis confirms that there is a significant correlation between the monthly area burned in Central Portugal and the number of days with thermal low conditions.

The climatic changes which are developing on a global scale, will significantly influence the intensity of wildfires and consequently the area burned, in many parts of the world. Model calculations indicate that the subtropical Mediterranean climate will be shifted to a climate strengthened in its subtropical character, at least in the southernmost Mediterranean region as pointed out by Hoinka *et al*. [2007b]. In this sense, in a changing climate the increase of frequency of the regional weather patterns mostly related to forest fires in Portugal may have important consequences at all environmental, social and economic levels.

As stated, in this study the temporal and spatial evolution of the regional weather patterns most related to wildfires were discussed. In the next chapter the surface meteorological conditions that may explain the forest fire activity in Portugal are analysed.

# 3. Fire activity in Portugal: relationship to the weather and the FWI system

## 3.1. Introduction

The previous chapter identified the most relevant atmospheric patterns related to the occurrence of fire events in Central Portugal. The achieved results point to the important role of the meteorological parameters in the forest fire activity over Portugal. In this chapter this relationship will be further investigated.

Weather and climate play a crucial role in determining the fire regime of an area [Viegas and Viegas, 1994; Vásquez and Moreno, 1995; Pyne *et al*., 1996; Skinner *et al*., 1999; Kunkel, 2001; Viegas *et al*., 2001; Viegas *et al*., 2004; Pereira *et al*., 2005]. The fire regime in return is very sensitive to changes in climate [Piñol *et al*., 1998; Pausas, 2004]. Higher temperatures and lower relative humidity conditions generally correspond to increased area burned but not necessarily to higher fire starts.

Weather determines fuel moisture, influences lightning ignitions, and contributes to fire growth through wind action. However, the long term average of area burned over a landscape is determined by a complex set of variables including the size of the sample area, topography, fragmentation of the landscape (rivers, lakes, roads, agricultural land), fuel characteristics, season, latitude, fire suppression policies and priorities, fire site accessibility, ignitions (people and lightning), and simultaneous fires, as well as the weather [Flannigan *et al*., 2005a]. Worldwide, important relationships between weather and forest fires have been established [Harrington *et al*., 1983; Flannigan and Harrington, 1988; Viegas *et al*., 1992; Viegas and Viegas, 1994]. In Canada, weather/climate has been pointed as the most important natural factor influencing forest fires [Stocks and Street, 1983; Flannigan and Wotton, 2001; Hely *et al*., 2001].

Although some important work has been done on this topic, in southern Europe the relationship between forest fires and weather conditions still needs further investigation. Over the West and East coast of the Iberian Peninsula some studies have already discussed this relationship. Pausas [2004] analysed the link between forest fire occurrence and climatic variables in the Valencia region of Spain and concluded that summer rainfall is an important factor for determining the amount of area burned in that region. The author also concluded that although fire ignitions may be determined by human factors, some of the variability in the annual area burned is explained by climatic parameters. Piñol *et al*. [1998] concluded that, in northeast Spain, a significant relationship exists between the number of very high fire risk days and the number of forest fires and area burned. Additionally, the authors pointed out that the number of forest fires and area burned increased from 1968 to 1994 due to a changing climate namely in what concerns an increase in temperature and aridity. In Portugal, Viegas *et al*. [1992] and Viegas and Viegas [1994] established a clear dependency of area burned and forest fire occurrence on weather variables. Analysis of the annual area burned in Portugal from 1975 to 1992 and precipitation amounts registered in Coimbra [Viegas and Viegas, 1994] indicated an exponential law relation ($r^2$=0.503) between annual area burned in Portugal and the total rainfall at the Coimbra meteorological station from May to September. The authors also stressed that the rainfall in the beginning of the fire season, namely in June, has a marked importance in the reduction of the area burned.

The use of fire rating systems is a widespread methodology to assess fire danger over a specific region of the globe. Viegas *et al*. [1999] pointed out that the Canadian Fire Weather Index (FWI) System is one of the most adequate fire risk assessment tools for southern European countries namely for Portugal. The FWI System is applied since 1998 by the national authorities to forecast the fire risk over Portugal. Viegas *et al*. [2004] described a methodology for calibrating the fire danger based on the daily FWI index, number of fires and area burned for each district of Portugal, which was applied for the summer period, between June and September, from 1988 to 1996. The analysis of the number of fires, area burned, and the FWI for each district showed that the range of variation of each of these parameters differed from district to district, which explains the necessity of a specific scale of risk for each parameter. In addition, Viegas *et al*. [2004] discussed the interannual variability of the area burned. The drought code (DC) component of the FWI System was correlated to the annual area burned and significant relationships were established.

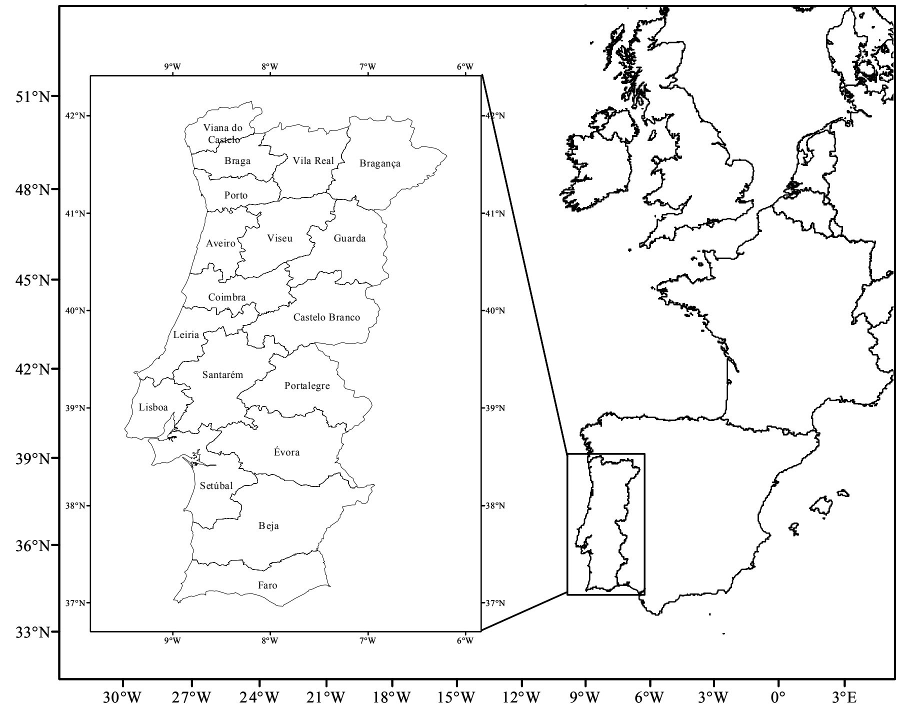
For this study, an updated statistical analysis is performed in order to consider the most recent forest fire data that were not considered in the previous studies. In this chapter, the main objective is to perform a spatial/temporal analysis of the area burned and the number of fires in Portugal, at the district level, based on the historical datasets from 1980 to 2004. In the subsequent chapters, these relationships will be used to predict the area burned and the number of fire starts, in Portugal, under future climate change scenario.

## 3.2. Data and Methods

This section describes the Portuguese characteristics relevant for this analysis understanding – *Study area description*. The forest fire statistics between 1980 and 2004 are discussed in *Forest fire database*. The compiled meteorological variables and the selected stations are presented under the *Meteorological data* topic. Finally, the *Canadian Fire Weather Index (FWI) System* is briefly described.

### 3.2.1. Study area description

Forested lands in Portugal occupy 5.4 millions of hectares and represent two-thirds of Portugal's surface area [DGRF, 2006a]. Eleven percent of the Portuguese territory is occupied by Maritime Pine stands or lands (*Pinus pinaster*), followed by Eucalypt (*Eucalyptus globulus*) (8 %) and Cork Oak (*Quercus suber*) (8 %). The Holm Oak (*Quercus rotundifolia*) represents 5 %, and the oak tree (*Quercus faginea*) and Stone Pine (*Pinus pinea*) exhibit 1 % each. Figure 3.1 shows the Portuguese districts identification and the dominant forest types. Maritime Pine is mostly common in the Castelo Branco, Coimbra, Leiria and Viseu districts. Castelo Branco, Aveiro and Santarém districts have higher forest lands of Eucalypt. On the other hand, the southern districts of Évora, Portalegre, Santarém and Setúbal have the majority of the Cork Oak in Portugal. The oak tree is most common in the northern districts of Vila Real, Bragança, and Guarda.




| District name | Dominant forest type (% district area) |
|---|---|
| Bragança | Maritime Pine (5%) |
| Vila Real | Maritime Pine (17%) |
| Viana do Castelo | Maritime Pine (17%) |
| Braga | Eucalyptus (16%) |
| Porto | Eucalyptus (18%) |
| Aveiro | Eucalyptus (25%) |
| Viseu | Maritime Pine (23%) |
| Guarda | Maritime Pine (12%) |
| Coimbra | Maritime Pine (30%) |
| Castelo Branco | Maritime Pine (24%) |
| Leiria | Maritime Pine (30%) |
| Santarém | Cork Oak (18%) |
| Portalegre | Cork Oak (23%) |
| Lisboa | Eucalyptus (10%) |
| Setúbal | Cork Oak (25%) |
| Évora | Holm Oak (20%) |
| Beja | Holm Oak (16%) |
| Faro | Cork Oak (8%) |

Figure 3.1 – Location of Portugal in the Iberian Peninsula, Portuguese districts identification and dominant forest types as a percentage of district area.

The Portuguese population is mainly concentrated in the urban and sub-urban areas of the coastal regions. The north region contains 35 % of the population, the Lisbon area 26 % and the central part 23 %. The remaining Portuguese regions have occupation levels below 8 % [INE, 2003]. This represents a considerable population asymmetry that certainly influences forest fire ignitions and spreading.

Some aspects of the property regime in the north and centre of Portugal, namely the high number of land owners (most of them unknown) and the absence of adequate property records, have important negative consequences concerning forest management. An increase of population within the forested lands greatly enhances the forest fire risk and, consequently, the destruction of goods and human lives and creates difficulties for the fire fighting operations. Land abandonment, due mainly to the aging of the land owners, also creates difficulties in the management of forested properties, leading to an increase in the fuel load and consequently in forest fire risk. In the southern part of the country the districts of Beja, Évora and Portalegre have a different demographic pattern. The populations are more concentrated and not spread among the forested areas, additionally the dominant forest types are resistant to forest fires. These are the regions of Portugal which reach the highest temperatures during the summer period and have lower precipitation rates throughout the year.

### 3.2.2. Forest fire database

The forest fire database for Portugal used in this study comprises the period between 1980 and 2004. The data were provided by the *Direcção Geral dos Recursos Florestais – DGRF* (General Directorate of Forestry Resources). This database constitutes the national component of the European Forest Fire Information System (EFFIS) created by the European Commission in 1994. The Commission Regulation (EC) 804/94 (now expired) established a Community system of information on forest fires for which a systematic collection of a minimum set of data on each fire occurring, the so-called "Common Core", had to be carried out by the Member States participating in the system. According to the currently in force Forest Focus, Regulation (EC) 2152/2003, concerning monitoring of forests and environment interactions in the community, the forest fire common core data should continue to be recorded and notified in order to collect comparable information on forest fires at the Community level.

At national level, the recorded information includes daily area burned and daily number of fires per district, among other variables. From 1980 to 2004, the dataset record illustrates a total of $2.7 \times 10^6$ ha of area burned, approximately 30 % of Portugal's total area, and 430,000 of forest fire occurrences. The DGRF database is based on *in situ* information provided by the Ministry of Agriculture and the National Civil Protection Service. Since 1990, the annual area burned is mapped based on satellite information.

Simple statistics for forest fire activity in Portugal were performed in order to better understand its main characteristics in terms of spatial and temporal distribution. Figure 3.2 represents the annual area burned and number of fires between 1980 and 2004. The maximum number of annual forest fires occurred in 1995, 1998, and 2000, that surpassed 30,000 occurrences. In terms of area burned the year of 2003 reached the highest value ever registered – 430,000 ha. It is interesting to observe that between 1980 and 2000 the annual number of forest fires regist an increase from year to year except in some specific years. In addition to this and according to the Portuguese Meteorological Institute since 1974 there is a clear increase in the average temperature values above Portugal. The years of 1995, 1997, 1998 and from 2000 to 2006 present higher average temperatures than the normal. From 1995 to 2000 the number of forest fires register a clear increase, although since 2001 they tend to remain almost constant.

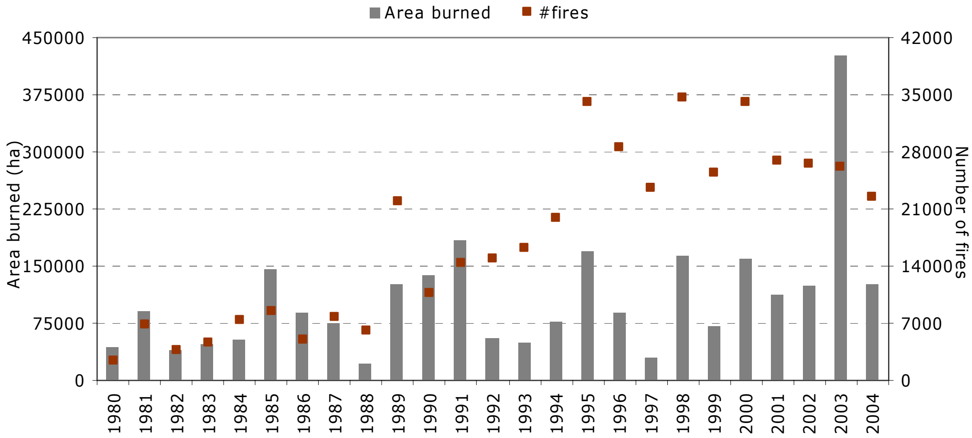



Figure 3.2 - Annual area burned (bars) and number of fires (square points) in Portugal between 1980 and 2004.

Figure 3.3 shows the monthly and the district distribution of the area burned and the number of fires between 1980 and 2004. The number of fire occurrences in the months of June (8 %), July (22 %), August (32 %), and September (20 %) represent 82 % of the yearly total (Figure 3.3a). The area burned peak is observed in August accounting for 45 % of the yearly total (Figure 3.3a) with the districts of Guarda, Castelo Branco, Viseu, and Coimbra presenting the highest area burned values in Portugal (Figure 3.3b). According to the National Plan for Forest Fires Prevention, the ignitions peak occurs along the weekend, and especially during the afternoon, denoting an important human influence on fire starts [APIF, 2005].

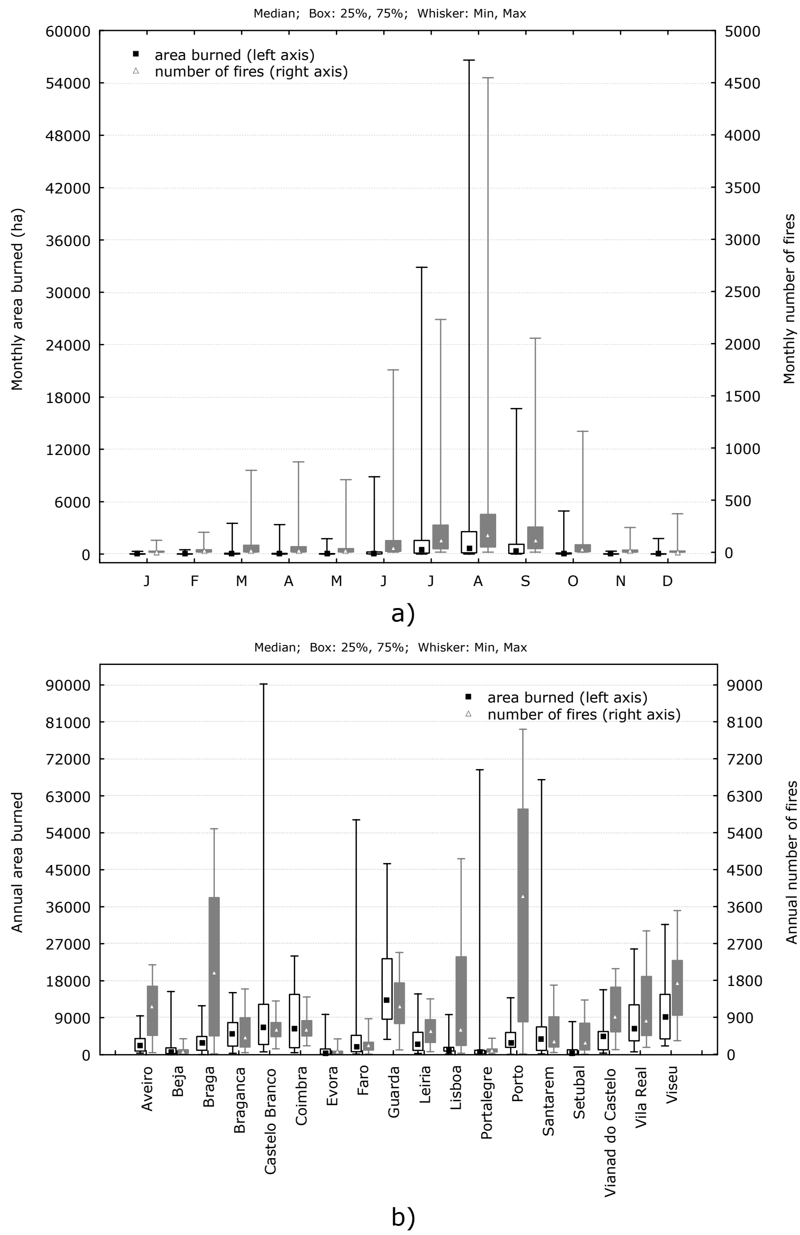



Figure 3.3 - Area burned (black) and number of fires (grey) a) by month and b) by Portuguese district, between 1980 and 2004.

The annual number of forest fires is higher in the most urban and sub-urban districts (Aveiro, Braga, Lisboa, Porto, Viana do Castelo, and Setúbal) (Figure 3.3b). In terms of forest fire occurrences, the Porto district (urban/sub-urban region) represents the highest percentage of fire occurrences in the last 25 years reaching almost 22 % of the total. Additionally, the Guarda district (rural region) accounts for almost 18 % of the area burned in Portugal, followed by Castelo Branco with 11 % (Figure 3.4).

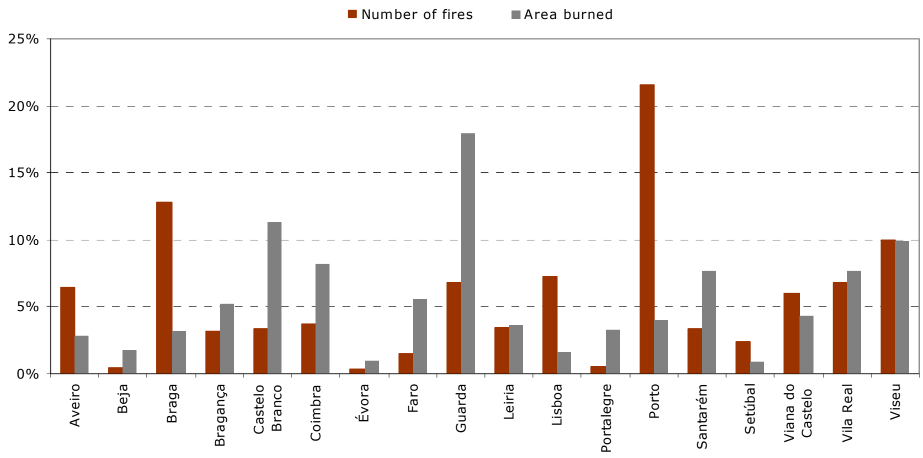



Figure 3.4 - Percentage of area burned and number of fires, for the period 1980-2004, by Portuguese district.

An analysis performed for the period between 1993 and 2003 revealed that 97 % of the forest fire ignitions were due to human influence with 37 % to arson, 28 % to negligence, and 32 % to unknown causes [APIF, 2005]. Arson is mainly related to fraud, hunting conflicts, and building construction interests, and is most notorious in the northern part of the country especially in the coastal regions. Negligence is the most important cause in the south mainly due to clearance activities. In the southern districts of Beja, Évora, and Portalegre the principal cause of negligence is related to agricultural machinery use. Specific regional characteristics are also responsible for forest fires starts such as fireworks activity in the northern districts of the country [APIF, 2005]. Portugal, like the majority of the southern European countries, has fewer forest fires due to natural causes because phenomena such as lightning have a low frequency of occurrence during the summer period.

### 3.2.3. Meteorological data

Data for daily maximum temperature, daily mean temperature, relative humidity, wind speed, and total rainfall from 1980 to 2004 were compiled. Twelve stations were analyzed over Portugal covering the majority of the territory except the northwest region for which there were no available data. Table 3.1 presents the considered stations and their principal characteristics.

Table 3.1 – Main characteristics of the meteorological stations considered in this study.

| Station name | Latitude (deg N) | Longitude (deg W) | Altitude (m) | Starting date | Ending date | # years |
|---|---|---|---|---|---|---|
| Bragança | 41.80 | 6.73 | 690 | Jan 80 | Dec 04 | 25 |
| Vila Real | 41.27 | 7.72 | 561 | Jan 80 | Dec 04 | 25 |
| Porto | 41.23 | 8.68 | 70 | Jan 80 | Dec 04 | 25 |
| Viseu | 40.67 | 7.90 | 443 | May 82 | Oct 04 | 23 |
| Coimbra | 40.15 | 8.47 | 171 | Jan 80 | Dec 04 | 25 |
| Castelo Branco | 39.83 | 7.48 | 386 | May 85 | Dec 04 | 19.5 |
| Portalegre | 39.28 | 7.42 | 597 | Jan 80 | Dec 04 | 25 |
| Santarém | 39.25 | 8.70 | 54 | Jan 80 | Dec 94 | 15 |
| Lisboa | 38.72 | 9.15 | 77 | Jan 80 | Dec 04 | 25 |
| Évora | 38.57 | 7.90 | 309 | Jan 80 | Dec 04 | 25 |
| Beja | 38.02 | 7.87 | 246 | Jan 80 | Dec 04 | 25 |
| Faro | 37.02 | 7.97 | 8 | Jan 80 | Dec 04 | 25 |

Some of the studied stations were lacking data for the full period under analysis (Santarém, Castelo Branco, and Viseu). From 1980 until the end of 2004, Viseu station only presented data from May to October. The majority of the meteorological data were supplied by the Portuguese Meteorological Institute (maximum temperature, dry bulb temperature, wet bulb temperature, rainfall, and wind speed). Some stations were missing data for short periods and these were filled using the National Climatic Data Centre (NCDC) database [NCDC, 2006].

### 3.2.4. The Canadian Fire Weather Index (FWI) System

The Canadian Forest Fire Weather Index (FWI) System is a system that monitors forest fire risk and supplies information to support fire management. The components of the FWI System can be used to predict fire behaviour and can be used as a guide to policy-makers in developing actions to protect life, property and the environment.

The FWI system was developed for Canadian forests but has also been applied in other countries and environments such as Mexico, southeast Asia, Florida and Argentina [Moriondo *et al.*, 2006]. For the Mediterranean basin, several studies showed that the FWI system and its components were well suited to the estimation of fire risk for the region [Viegas *et al.*, 1999]. Moreover, the FWI is currently the fire risk index used by the Joint Research Centre (JRC) to map fire risk at the European Union level [JRC, 2006]. The success of this system is due both to the simplicity of its calculation procedures and to the simulation of the moisture of a generalized fuel type, which has been successfully applied to model fire potential in a broad range of fuel types [Van Wagner, 1987].

The FWI System is a weather-based system that models fuel moisture using a dynamic approach that tracks the drying and wetting of distinct fuel layers in the forest floor [Van Wagner, 1987]. The FWI is based on the moisture content of three classes of forest fuel plus the effect of the wind on fire behaviour. The FWI System comprises six components. The first three are fuel moisture codes that follow daily changes in the moisture content of three classes of forest fuel with different drying rates. The last three components are fire behaviour indexes representing rate of spread, fuel weight consumed, and fire intensity. Their values rise as the fire danger increases. The system only depends on weather variables. The 12 Local Standard Time (LST) observations of temperature, relative humidity, wind speed, and 24-h precipitation are the inputs required to calculate the components of the FWI System. Figure 3.5 presents the FWI flowchart.

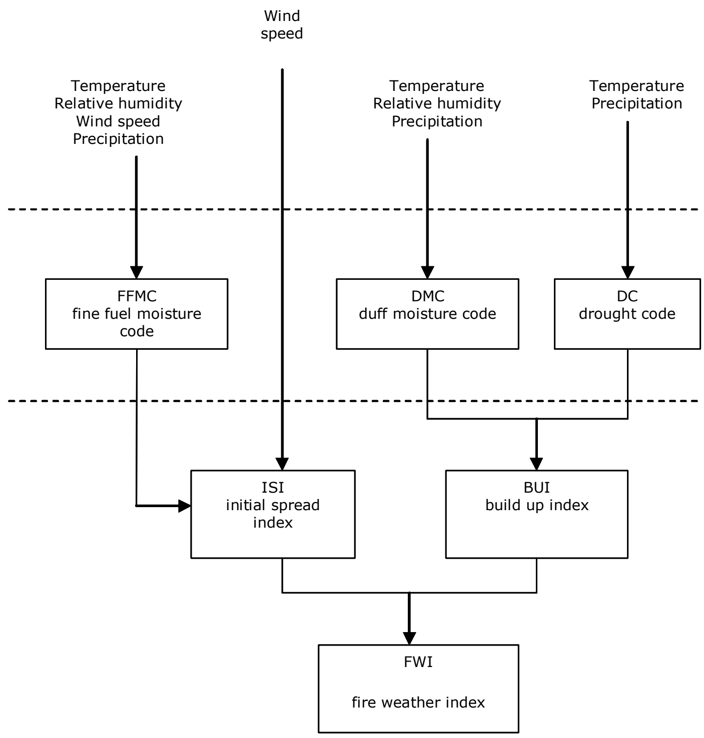



Figure 3.5 – Canadian Fire Weather Index (FWI) System components
[adapted from Van Wagner, 1987].

As described, there are three moisture codes that represent the moisture content of fine fuels (fine fuel moisture code, FFMC), loosely compacted organic material (duff moisture code, DMC), and a deep layer of compact organic material (drought code, DC). They are arranged in code form with values rising as moisture content decreases.

- FFMC – represents the moisture content of litter and other fine fuels. Indicates the relative ease of ignition and flammability of fine fuels. Thus, can be used as an indicator of ignition potential or the potential for fires to start and spread in the area
- DMC – is a numeric rating of the average moisture content of loosely compacted organic layers of moderate depth. This code gives an indication of fuel consumption in moderate duff layers and medium-size woody material.
- DC – indicates the moisture content of a deep layer of compact organic matter. This code is a useful indicator of seasonal drought effects on forest fuels and the amount of smoldering in deep duff layers. It can also be used as an indicator of difficulty in extinguishing deep burning fires.

These moisture indexes are combined to create a generalized index of the availability of fuel for consumption (build up index, BUI). The FFMC is combined with wind speed to estimate the potential spread rate of a fire (initial spread index, ISI).

- BUI – is a numeric rating of the total amount of fuel available for combustion. It combines the DMC and the DC.
- ISI – is a numeric rating of the expected rate of fire spread. It combines the effects of wind and the FFMC on rate of spread without the influence of variable quantities of fuel.

The BUI and ISI are combined to create the FWI which is an estimate of the potential intensity of a spreading fire. The daily severity rating (DSR) is a simple exponential function of the FWI intended to increase the weight of higher values of FWI in order to compensate for the exponential increase in area burned with fire diameter [Williams, 1959; Van Wagner, 1970].

- FWI – is a numeric rating of fire intensity. It combines the ISI and the BUI. It is suitable as a general index of fire danger throughout the forested areas. Indicates the difficulty of fire control based on the head fire intensity and fire fighting capability.

- DSR – is a numeric rating of the difficulty of controling fires. It is based on the Fire Weather Index but more accurately reflects the expected efforts required for fire suppression.

A very important issue is the calibration of the FWI System for other regions than Canada. Viegas *et al*. [2004] conducted the calibration of the FWI component for Portugal based on the daily area burned and daily number of fires registered in each Portuguese district. Table 3.2 shows the FWI limit values and the corresponding fire danger classes for each district.

Table 3.2 – FWI limit values for the fire danger classes by Portuguese district [Viegas *et al*., 2004].

| **Districts** | **Danger classes** | | | | |
|---|---|---|---|---|---|
| | **Low** | **Moderate** | **High** | **Very High** | **Extreme** |
| Viana do Castelo | <10 | 15 | 30 | 45 | >45 |
| Braga | <10 | 15 | 30 | 50 | >50 |
| Porto | <8 | 15 | 25 | 40 | >40 |
| Vila Real | <13 | 20 | 30 | 50 | >50 |
| Bragança | <23 | 30 | 45 | 55 | >55 |
| Aveiro | <10 | 17 | 23 | 40 | >40 |
| Viseu | <15 | 25 | 45 | 70 | >70 |
| Guarda | <8 | 15 | 25 | 50 | >50 |
| Coimbra | <15 | 22 | 30 | 45 | >45 |
| Leiria | <15 | 25 | 30 | 50 | >50 |
| Castelo Branco | <20 | 35 | 45 | 60 | >60 |
| Lisboa | <25 | 35 | 50 | 70 | >70 |
| Santarém | <25 | 33 | 50 | 60 | >60 |
| Setúbal | <30 | 40 | 55 | 70 | >70 |
| Portalegre | <35 | 50 | 65 | 75 | >75 |
| Évora | <40 | 50 | 65 | 75 | >75 |
| Beja | <40 | 50 | 65 | 75 | >75 |
| Faro | <30 | 40 | 60 | 75 | >75 |

For the purposes of this study, the FWI System components were computed using daily mean values of temperature, relative humidity, wind, and daily total precipitation. In order to evaluate the relationship between daily mean and noon values, the FWI index was computed at 12 LST and on a daily average basis for

Coimbra and Portalegre stations (stations for which noon weather data were available). Coimbra and Portalegre stations presented a Pearson coefficient above 0.93 ($p<0.0001$), with a negative bias between the daily mean FWI and the FWI computed at noon of -3.5 and -2.4, respectively, indicating a slight underestimation. Based on these relationships, it was concluded that the mean daily values were suitable to be applied in this study.

The Statistical Analysis System (SAS) version 9.1.3 [SAS, 2004] was used for the FWI System components estimation and for all the statistical analyses carried out. All the analyses were performed at a 0.05 significance level. Averages of the meteorological variables and the FWI System components were calculated for monthly and seasonal (May 1st to October 30th) periods. Extremes of the variables (maximum and 90th percentile) were also calculated because the majority of the area burned occurs during extreme fire weather conditions [Pereira *et al*., 2005].

The natural logarithm of the area burned (ha) and the natural logarithm of the number of fires were used to normalize, respectively, the area burned and the number of fires, because the raw data distribution is non-normal. A unit was added to the observed area burned and to the number of fires in order to avoid the zero values in the logarithmic calculation. A correlation matrix was constructed for each district and for each period (daily, monthly, and seasonal) with the natural logarithm of area burned and the natural logarithm of the number of fires considering the variables listed in Table 3.3. All variables listed in Table 3.3 were then introduced in the forward stepwise regression [Wilks, 1996] and the terms were accepted only if they met the 0.05 significance level.

Table 3.3 - Meteorological and FWI System variables.

| | |
|---|---|
| FFMC | Mean fine fuel moisture code |
| FFMCX | Maximum fine fuel moisture code |
| FFMCP90 | 90th percentile of fine fuel moisture code |
| DC | Mean drought code |
| DCX | Maximum drought code |
| DCP90 | 90th percentile of drought code |
| DMC | Mean duff moisture code |
| DMCX | Maximum duff moisture code |
| DMCP90 | 90th percentile of duff moisture code |
| BUI | Mean build up index |
| BUIX | Maximum build up index |
| BUIP90 | 90th percentile of build up index |
| ISI | Mean initial spread index |
| ISIX | Maximum initial spread index |
| ISIP90 | 90th percentile of initial spread index |
| FWI | Mean fire weather index |
| FWIX | Maximum fire weather index |
| FWIP90 | 90th percentile of fire weather index |
| DSR | Mean daily severity ratio |
| DSRX | Maximum daily severity ratio |
| DSRP90 | 90th percentile of daily severity ratio |
| TX | Mean of maximum daily temperatures (°C) |
| TXX | Maximum of maximum daily temperatures (°C) |
| TXP90 | 90th percentile of of maximum daily temperatures (°C) |
| TPREC | Total precipitation (mm) |

## 3.3. Results and Discussion

In this section the statistical analysis between the forest fire activity, the weather data and the FWI System components from 1980 to 2004 is presented and discussed – *Statistical analysis*. Moreover, the obtained statistical models were applied to the year 2005 in order to evaluate their performance in the prediction of the area burned and the number of fires – *Validation procedure*.

### 3.3.1. Statistical analysis

Daily, monthly, and seasonal (May 1st to October 30th) analysis were performed in order to assess the best temporal resolution for the regression analysis. Pearson correlation coefficients (r) were computed for the different temporal resolutions and the obtained results are presented in Appendix A. The correlation procedure established that the best results were obtained on a monthly basis compared to daily and seasonal periods (Appendix A). Table 3.4 and Table 3.5 present the results from the forward stepwise regression of the monthly area burned and the monthly number of fires for the twelve districts across Portugal. All the variables listed in Table 3.3 were available for the stepwise regression but only the significant ones were kept. The selected significant variables are arranged by order of importance. The analyzed districts shown in Table 3.4 and Table 3.5 are organized from north to south. The averages and extremes of the DC, BUI, DMC, FWI, DSR, and FFMC components, and the temperature and the relative humidity were the selected significant variables by the stepwise regression, depending on the district. Mean or maximum temperature was selected by all districts in the north and central regions except Vila Real and Santarém. For the southern districts of Évora and Beja, the FWI index was selected as the best predictor for area burned. The FWI was also selected for almost all the districts except Bragança, Porto and Faro. For the number of fires the mean and maximum temperature is the first order selection by almost all districts except Vila Real, Portalegre, Santarém, and Évora.

Table 3.4 - District monthly area burned explained variance ($r^2$) and variables selected, in order of importance, by forward stepwise regression.

| **District** | **Significant variables** | **Explained variance (%)** | **N** | **p** |
|---|---|---|---|---|
| Bragança | TX, DC, BUI | 63.3 | 300 | <0.0001 |
| Vila Real | FWIP90, FFMC, DC, RH | 67.9 | 300 | <0.0001 |
| Porto | DMCX, TXX, FFMC | 65.4 | 300 | <0.0001 |
| Viseu | DCX, FFMC, FWIX, TXX | 80.4 | 138 | <0.0001 |
| Coimbra | FWI, TXX, DC | 72.6 | 300 | <0.0001 |
| Castelo Branco | FWIP90, BUI, TX | 75.6 | 236 | <0.0001 |
| Portalegre | FWI, TXX | 45.6 | 300 | <0.0001 |
| Santarém | FWI, DSRX | 78.5 | 180 | <0.0001 |
| Lisboa | TXX, DC, FWI | 68.4 | 300 | <0.0001 |
| Évora | FWI | 43.1 | 300 | <0.0001 |
| Beja | FWIP90 | 57.8 | 300 | <0.0001 |
| Portalegre, Évora, Beja | FWIP90, TX | 60.9 | 300 | <0.0001 |
| Faro | DC, DSR, TXP90 | 69.9 | 300 | <0.0001 |
| All districts | FWIP90, RH, DC | 80.4 | 300 | <0.0001 |

Table 3.5 - District monthly number of fires explained variance ($r^2$) and variables selected, in order of importance, by forward stepwise regression.

| **District** | **Significant variables** | **Explained variance (%)** | **N** | **p** |
|---|---|---|---|---|
| Bragança | TX, DC | 53.3 | 300 | <0.0001 |
| Vila Real | BUIP90, FFMCX, DC, | 58.3 | 300 | <0.0001 |
| Porto | TXX, RH, DMCX | 56.9 | 300 | <0.0001 |
| Viseu | TXX, DCX, FWIX | 71.8 | 138 | <0.0001 |
| Coimbra | TXX, FFMC, BUIP90 | 69.1 | 300 | <0.0001 |
| Castelo Branco | TX, FFMC, BUI | 67.7 | 236 | <0.0001 |
| Portalegre | RH, DCX | 39.8 | 300 | <0.0001 |
| Santarém | FWI, DCX, FWIP90 | 77.0 | 180 | <0.0001 |
| Lisboa | TXX, DC | 49.1 | 300 | <0.0001 |
| Évora | FWIX, RH | 36.5 | 300 | <0.0001 |
| Beja | TX, FWIX | 44.5 | 300 | <0.0001 |
| Portalegre, Évora, Beja | TXX, RH, DC | 47.9 | 300 | <0.0001 |
| Faro | TX, FFMCP90, DMCP90 | 56.1 | 300 | <0.0001 |
| All districts | TXX, RH, DCP90 | 64.7 | 300 | <0.0001 |

The explained variance ranges from 43.1 % to 80.4 % for the area burned and 36.5 % to 77.0 % for the number of fires, depending on the district, and all regressions are highly significant ($p<0.0001$). The districts under evaluation accounted for 48 % in terms of the total area burned and 56 % for the number of fires between 1998 and 2004. In this work, the Guarda district, an important Portuguese district in terms of area burned (18 % of the total area burned in Portugal in the last 25 years), was not considered due to lack of meteorological data for the 1980-2004 period. In the districts of Évora, Beja, and Portalegre, the area burned accounted for 17.7 % of the total and the number of fires accounted for 4.8 % of the total. The FWI and the temperature were the best predictors for the area burned in these districts.

According to Table 3.4 and Table 3.5, the significant variables that explained the majority of the variance in both area burned and number of fires differ, although most of the significant variables could be found in all districts and in both regressions except Portalegre. The temperature and the FWI index are selected by almost all districts giving an indication on the FWI reliability as a fire rating system in Portugal. In addition, the DC index is also present in the majority of the obtained significant variables. These results are in agreement with the findings of Viegas *et al*. [2004].

The achieved results point to an interesting north/centre *vs.* south dichotomy in terms of fire weather. For the southern districts fewer significant variables were selected in the regression models. These findings may be supported by the different local physical conditions that explain this behaviour. The type of forest and shrubland, in addition to the population distribution can also explain the forest fire behaviour in the different Portuguese regions. All districts in north and central regions exhibited variances above 60 % and above 50 % for area burned and number of fires, respectively. The highest correlation was found in the Viseu district, reaching 80.4 %. Nevertheless, it should be noted that the number of values used in the regression model was the lowest among all analyzed districts (Table 3.1, pp 39). The highest explained variance for the number of fires was in the Santarém district reaching 77 %. Santarém district only presents 15 years of meteorological data (Table 3.1).

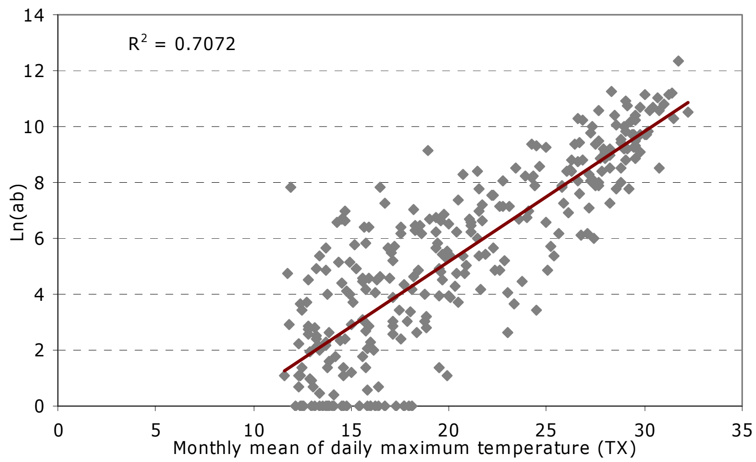
Portalegre, Évora and Beja districts exhibit lower explained variance values and also present the lowest values of area burned and number of fires. In these districts the temperatures can reach very high values (up to 40 ºC) associated with low relative humidity but the fuel characteristics like forest density and the physical conditions are different from the rest of the country. The typical forest in this part of the country (Cork Oak and Holm Oak) is mainly characterized by fire resistant species. In this context, it seemed appropriate to group these three districts. According to this new analysis the monthly mean of daily maximum temperature (TX) and the FWI 90$^{th}$ percentile explained 60.9 % of the area burned (Table 3.4) whereas the monthly means of the drought code (DC), and the relative humidity (RH), and the monthly maximum of daily maximum temperature (TXX) explained 47.9 % of the number of fires (Table 3.5). This group analysis significantly improved the variance explained in the area burned and the number of fires in this part of the country.

For the averaged Portuguese meteorological conditions based on the data from the twelve stations, the best predictors for the natural logarithm of area burned were the FWI 90$^{th}$ percentile, RH, and the DC, explaining 80.4 % of the variance in the area burned. The best predictors for the monthly number of fires were the TXX, the RH and the DC 90$^{th}$ percentile which explained 64.7 % of the variance (Table 3.4 and Table 3.5). It is interesting to note that the RH and the DC variables are selected in both regressions giving insight about the importance of the soil and the atmospheric humidity in the fire statistics over Portugal.

Figure 3.6 presents the relationship between the natural logarithm of monthly area burned and the natural logarithm of monthly number of fires against the monthly mean of daily maximum temperature (TX) for Portugal. Temperature alone explained

71 % of the variance in the area burned and 58 % in the number of fires. The temperature was not selected in the regression model but by itself, it exhibited a very good correlation with the area burned in Portugal.

Figure 3.6 demonstrates that the relationships were linear for the natural logarithm of area burned and the natural logarithm of the number of fires and is representative for all analyzed districts. In Figure 3.6, there are some data points with zero area burned and zero number of fires despite high temperatures; this may be related to the lack of ignitions in those months. It is obvious that notwithstanding very severe fire weather, there will be no area burned without an ignition and this might explain part of some of the unexplained variance in the obtained regressions [Flannigan *et al.*, 2005a].

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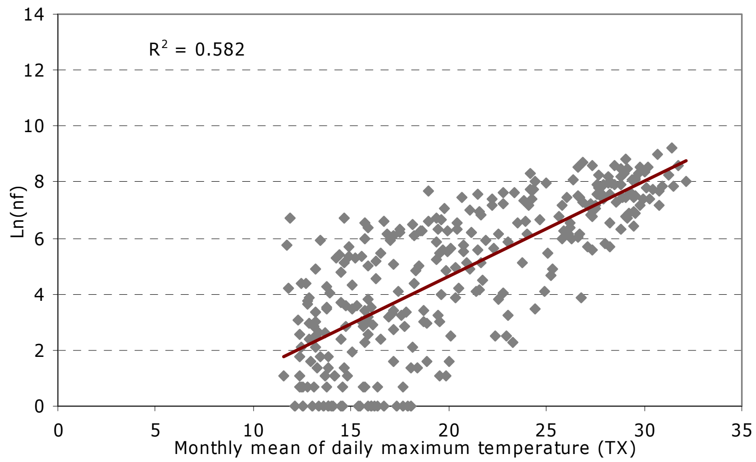
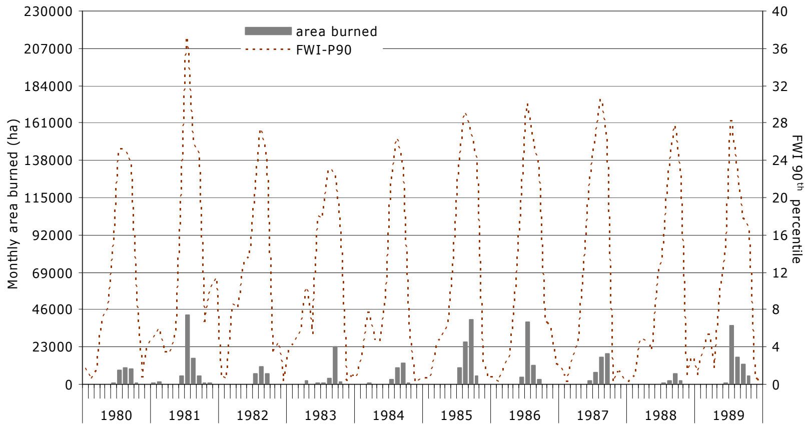



b)

Figure 3.6 - (a) Monthly area burned and (b) monthly number of fires *versus* monthly mean of daily maximum temperature (TX) in Portugal, from 1980 to 2004.

Figure 3.7 shows a detailed analysis of the relationship between the monthly area burned and the FWI 90$^{th}$ percentile in Portugal by decade.

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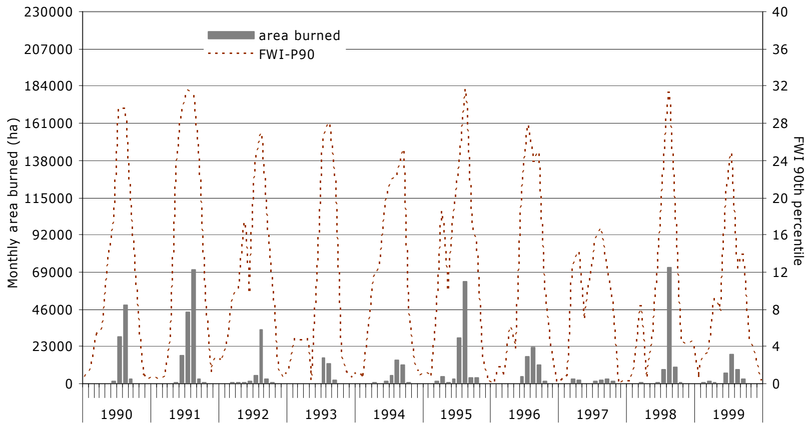


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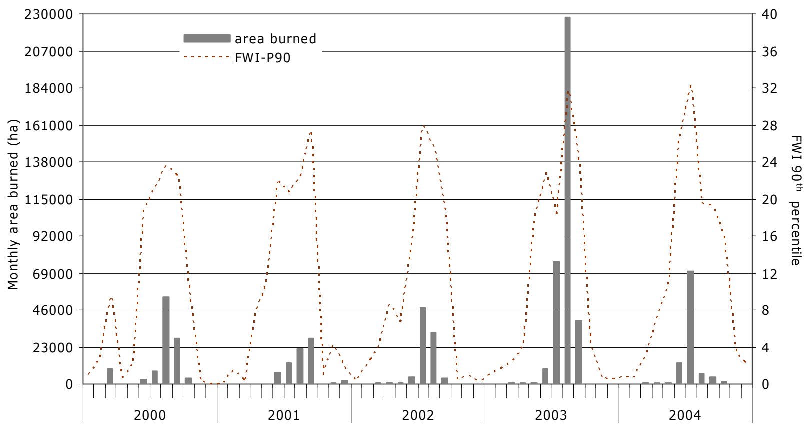



c)

Figure 3.7 - Monthly area burned and monthly 90$^{th}$ percentile of the daily FWI for the (a) 1980s, (b) 1990s and for (c) 2000-2004 period, over Portugal.

It is possible to find a clear relationship between the area burned and the FWI 90$^{th}$ percentile values. It should be noted that the year 2003, namely the month of August, represented an extreme event in terms of area burned in Portugal but the obtained FWI 90$^{th}$ percentile values did not reflect this fact. When the FWI 90$^{th}$ percentile values registered an increase this was accompanied by higher values on the area burned. On the other hand, the period 2000-2004 registered a clear increase on the area burned compared to the previous decades, although the FWI 90$^{th}$ percentile values did not exhibit this enhancement.

Table 3.6 and Table 3.7 present the regression models obtained for each analyzed district and for the average conditions over Portugal. The regressions obtained for the region formed by Portalegre, Évora and Beja district are also presented. All the terms were accepted at a 0.05 significance level. The obtained regression models constitute an adequate tool to diagnose the area burned and the forest fire occurrence in Portugal.

Table 3.6 - Regression model selected by stepwise regression for the natural logarithm of monthly area burned (TX and TXX in degrees Celsius).

| **District** | **Regression model Ln(ab)** | **p** |
|---|---|---|
| Bragança | $-1.803 + 0.206TX + 0.00232DC + 0.0104BUI$ | <0.0001 |
| Vila Real | $5.140 - 0.0678RH + 0.0274FFMC + 0.00379DC + 0.0956FWIP90$ | <0.0001 |
| Porto | $-4.589 + 0.0357FFMC + 0.161TXX + 0.0466DMCX$ | <0.0001 |
| Viseu | $-4.021 + 0.0412FFMC + 0.111TXX + 0.00547DCX + 0.0506FWIX$ | <0.0001 |
| Coimbra | $-1.824 + 0.00221DC + 0.301FWI + 0.102TXX$ | <0.0001 |
| Castelo Branco | $-1.164 + 0.124TX + 0.00921BUI + 0.0749FWIP90$ | <0.0001 |
| Santarém | $0.161 + 0.209FWI + 0.174DSRX$ | <0.0001 |
| Lisboa | $-2.700 + 0.00242DC + 0.0623FWI + 0.145TXX$ | <0.0001 |
| Portalegre/Évora/Beja | $-1.329 + 0.103TX + 0.0882FWIP90$ | <0.0001 |
| Faro | $-2.417 + 0.000750DC + 0.392DSR + 0.134TXP90$ | <0.0001 |
| All districts | $14.628 + 0.101FWIP90 - 0.156RH + 0.00299DC$ | <0.0001 |

Table 3.7 - Regression model selected by stepwise regression for the natural logarithm of monthly number of fires (TX and TXX in degrees Celsius).

| District | Regression model<br><br>Ln(nf) | p |
|---|---|---|
| Bragança | $-1.223 + 0.156TX + 0.00205DC$ | <0.0001 |
| Vila Real | $3.638 - 0.0712RH + 0.00239DC + 0.0402FFMCX + 0.00864BUIP90$ | <0.0001 |
| Porto | $4.273 - 0.0919RH + 0.206TX + 0.0347DMCX$ | <0.0001 |
| Viseu | $-2.157 + 0.141TXX + 0.00383DCX + 0.0406FWIX$ | <0.0001 |
| Coimbra | $-2.840 + 0.0352FFMC + 0.0826TXX + 0.0154BUIP90$ | <0.0001 |
| Castelo Branco | $-2.153 + 0.126TX + 0.0240FFMC + 0.00621BUI$ | <0.0001 |
| Santarém | $0.0443 + 0.0987FWI + 0.0525FWIP90 + 0.000585DCX$ | <0.0001 |
| Lisboa | $-3.004 + 0.00166DC + 0.189TXX$ | <0.0001 |
| Portalegre/Évora/Beja | $2.751 - 0.0436RH + 0.000950DC + 0.0591TXX$ | <0.0001 |
| Faro | $-7.358 + 0.148TX + 0.0651FFMCP90 + 0.00494DMCP90$ | <0.0001 |
| All districts | $11.477 + 0.0772TXX - 0.132RH + 0.00205DCP90$ | <0.0001 |

Using the regression equation for the average Portuguese conditions (from Table 3.6) the monthly area burned was estimated and plotted against the observed area burned (Figure 3.8). It is possible to verify a general trend to underestimate the monthly area burned in Portugal using the obtained regression equation. This underestimation is due to other factors than the weather and the FWI components, which are responsible for the unexplained variance in the area burned data.

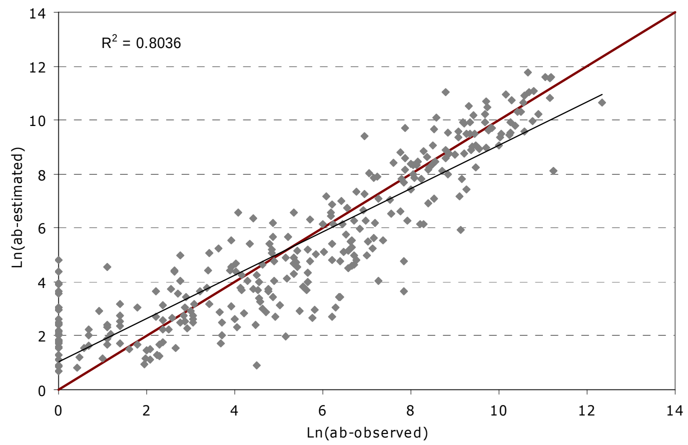
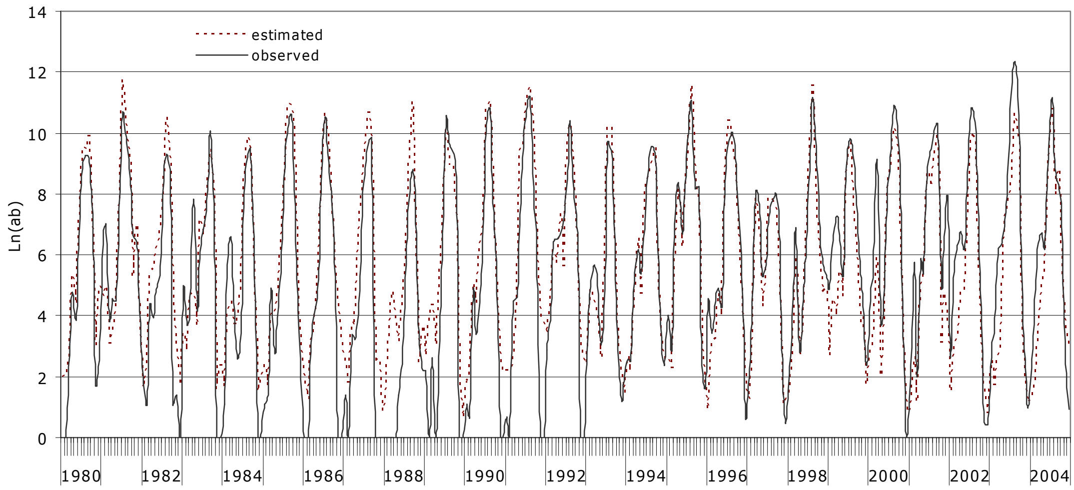



Figure 3.8 - Natural logarithm of the estimated monthly area burned *vs.* the natural logarithm of the observed monthly area burned, between 1980 and 2004. In red is drawn the 1:1 correlation line. The data trend line is represented in black.

Figure 3.9 shows a comparison between the estimated and the observed monthly area burned and number of fires in Portugal between 1980 and 2004.

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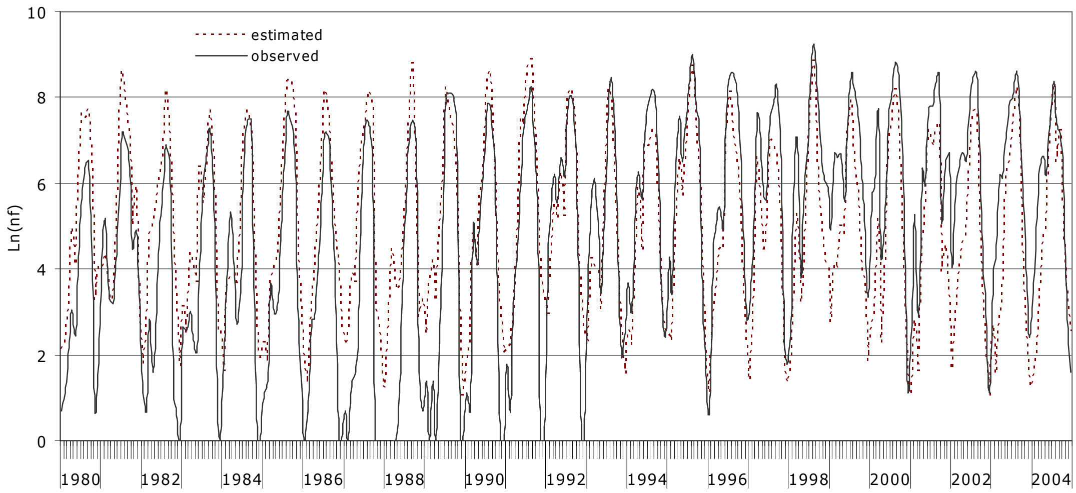



b)

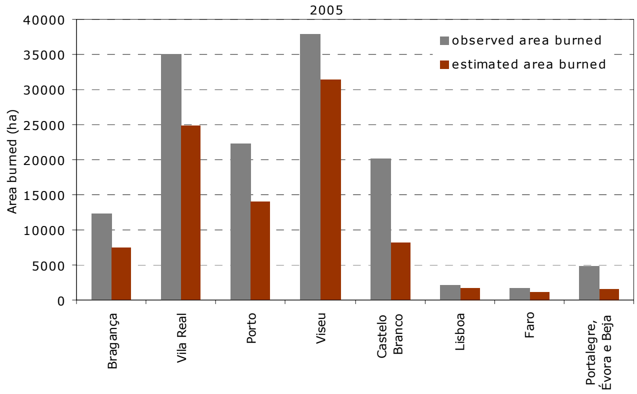
Figure 3.9 - Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires, between 1980 and 2004, over Portugal.

According to Figure 3.9a, from 1980 to 1993 there is a trend to overestimate the maximum and minimum values of the monthly area burned. Since 1999 the area burned over Portugal tends to be underestimated. The analysis of Figure 3.8 and Figure 3.9a indicates that the underestimation of the area burned in the last years of the analysis is stronger than the overestimation for the period between 1980 and 1993 leading to an overall underestimation of the area burned by the developed statistical model. The period between 2000 and 2004 has the highest average annual area burned of the overall analyzed period contributing to the enhancement of the differences between observed and estimated values. According to Figure 3.9b, the natural logarithm of the monthly number of fires is overestimated from 1980 to 1992. From 1993 the monthly number of fires are underestimated especially the minimum values.

Concerning the obtained statistics, each district has different fuel distributions with particular characteristics that may also explain some of the variance in the area burned and in the number of fires. The way the different districts deal with forest fire prevention and fire fighting is another reason for the unexplained variance. The prevention campaigns that each local authority implements are another aspect that influences the forest fire statistics. It should be stressed that the fuel characteristics were not explicitly treated, but implicitly, their expression is detected in the fire statistics. An important source of uncertainty is related to the meteorological data acquisition and forest fire data records. After 1992, the area burned data records are more precise.

### 3.3.2. Validation procedure

In order to evaluate the regression models exhibited in Table 3.6 and Table 3.7 the FWI system components were calculated for 2005 for the different districts. It was not possible to validate the regression models for the districts of Coimbra and Santarém due to lack of data for this period at the NCDC database. Figure 3.10 presents the annual area burned and annual number of fires validation for 2005.

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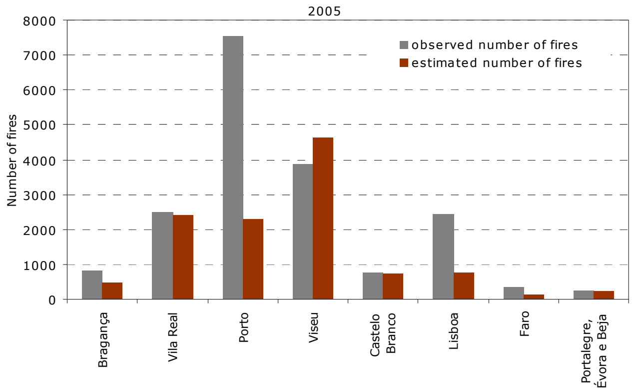
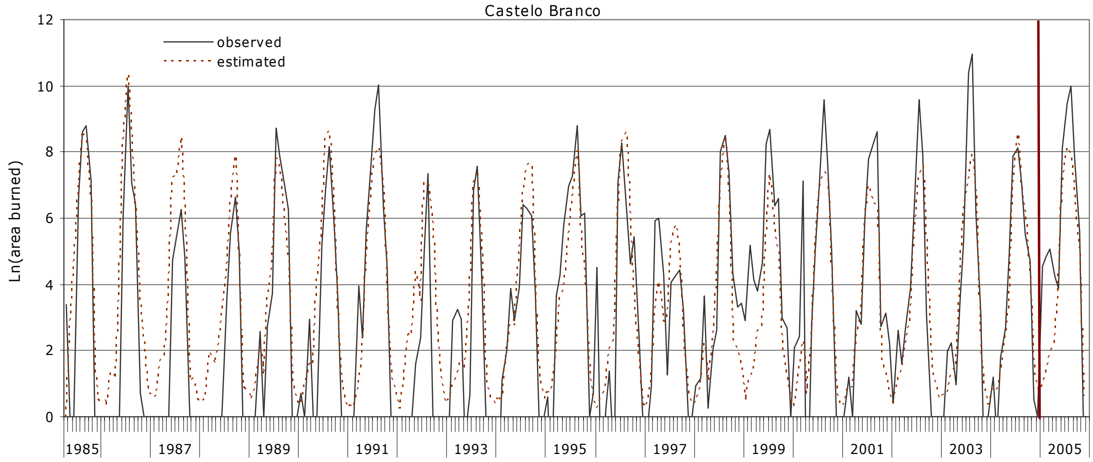



b)

Figure 3.10 - Observed and estimated annual a) area burned and b) number of fires, by district, during 2005.

The area burned and the number of fires are underestimated in almost all analysed districts. At Viseu the number of fires are overestimated and at Porto are clearly underestimated. The number of fires registered in 2005 in Porto is extreme when compared to the values registered between 1980 and 2004 (Figure 3.3). The year of 2005 was a critical year in terms of area burned in Portugal reaching almost 325,000 ha. This fact may explain at a certain extent the projections based on the obtained statistical models.

A detailed analysis, based on monthly data, was also performed. Considering the data availability between 1980 and 2005 at each meteorological station the FWI system components were calculated and monthly area burned and number of fires were estimated based on the obtained statistical models. The monthly data used to build the regression equations for the period 1980-2004 are presented as well as the monthly values of area burned, by district, for 2005 (independent data) in order to test the regression equations. As an example, Figure 3.11 presents the natural logarithm of the monthly area burned and the monthly number of fires for Castelo Branco. The comparisons concerning the other districts are collected in Appendix B.

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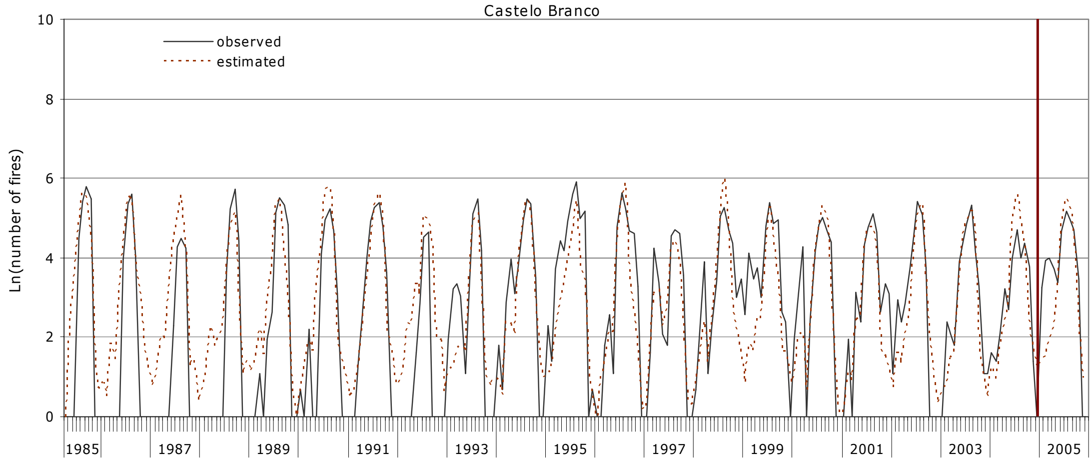



b)

Figure 3.11 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Castelo Branco district, from 1980 to 2005.

For all analysed districts it was possible to verify that the obtained regression models tend to underestimate the monthly area burned. This situation was more pronounced in the year 2003 especially in Castelo Branco (Figure 3.11). The districts of Bragança (Figure B.1), Faro (Figure B.2) and Lisboa (Figure B.4) and the region formed by Portalegre, Évora, and Beja (Figure B.3) also exhibit the same behaviour. As already stated the year 2003 was an extreme year in terms of fire activity in Portugal. In Bragança, Castelo Branco, and Vila Real districts the estimated area burned was always underestimated from 1998 to 2005. The number of fires were also underestimated in the majority of the analysed districts. Porto district showed the highest difference between observed and estimated number of fires (Figure B.7). The results point that other variables beyond the meteorological conditions are responsible for the number of fire starts in Porto district. This is the district that presents the highest number of forest fires in Portugal. Lisboa, Vila Real, and Bragança districts presented a clear underestimation of the number of fires between 1994 and 2002.

The performed validation for the year 2005 pointed out the main difficulty of the obtained regression models in correctly estimate the area burned and the number of fires for an extreme situation. Clearly this is closely dependent on the historical dataset used to develop the statistical models.

## 3.4. Summary and conclusions

The relationships among the weather, the Canadian Fire Weather Index (FWI) System components, and the monthly area burned, and the number of fire occurrences from 1980 to 2004, were investigated for twelve Portuguese districts. A statistical approach was used to estimate the monthly area burned and the monthly number of fires per district, using meteorological variables and the FWI System components as predictors. Results suggest that fire weather explains the majority of the variance of the area burned and the number of fires in Portugal. The approach succeeded in explaining from 60.9 % to 80.4 % of the variance for area burned and from 47.9 % to 77.0 % of the variance for the number of fires. All regressions were highly significant ($p<0.0001$).

Averages and extremes (maximum and 90$^{th}$ percentile) of the temperature, the DC and the FWI were selected for almost all districts giving an indication on the importance of these indexes on the fire statistics over Portugal. For the average conditions of the twelve Portuguese districts under analysis, approximately 80 % of the variance in area burned was explained by the FWI 90$^{th}$ percentile and by the monthly mean of RH and the DC. The number of fires explained variance reached almost 65 % and the selected variables by the stepwise regression method were the monthly maximum TX, the monthly mean RH and the DC 90$^{th}$ percentile. It is interesting to point that two meteorological variables (RH and TX) and one drought index (DC) explain the majority of the number of fires in Portugal. The relative humidity and two severity indexes (DC and FWI) are the selected significant variables for area burned indicating the importance of humidity and the long-term drought effect. The integrated index represented by the FWI 90$^{th}$ percentile was selected in the regression model giving an indication about the dependency of area burned on the intensity of the spreading fire.

Based on the obtained statistical models a validation procedure was attempted for the year 2005. The obtained results indicate a clear underestimation of the area burned and number of fires in the analysed districts. In Porto district this difference is more pronounced indicating that during 2005 other factors than meteorology contributed to the overall number of forest fire occurrences. This is the Portuguese district that regists the highest number of fire occurrences being this directly related to its urban/sub-urban characteristics that deeply affect the fire statistics in that region.

The results point to highly significant relationships among forest fires in Portugal and the weather and the Canadian FWI System. This analysis provides the baseline information for predicting the area burned and number of fires under future climatic scenarios and the subsequent impacts on air quality.

Having this in mind, in the next chapter the potential impacts of climate change on fire weather risk over Portugal will be analysed and the fire weather in a future climatic scenario will be discussed.

# 4. Fire weather risk in a future climatic scenario

## 4.1. Introduction

Forest fire risk is influenced by a large number of factors, including fuels, terrain, land management, suppression and weather (as shown in Chapters 2 and 3). Fire-weather risk relates to how a combination of weather variables influences the risk of a fire starting or its rate of spread, intensity or difficulty of suppression [Viegas *et al.*, 1999]. Worldwide important relationships between the weather and the forest fire activity were established [Harrington *et al.*, 1983; Viegas *et al.*, 1992; Viegas and Viegas, 1994; Flannigan and Harrington, 1988; Carvalho *et al.*, 2007a].

The existence of an observable warming trend in the world climate has become a well established fact in the last decade of the 20$^{th}$ century, where a significant number of the warmest years were observed [IPCC, 2007]. Over Portugal and since 1972, there is a general trend towards an increase in the mean annual surface air temperature. Additionally, spring accumulated precipitation has registered a systematic reduction, accompanied by slight increases in the other seasons [Santos *et al.*, 2002].

Regional climate change predictions indicate that the majority of the country is likely to become hotter and drier by the end of the XXI century [Christensen and Christensen, 2007; Santos *et al.*, 2002]. The Intergovernmental Panel on Climate Change report [IPCC, 2007] suggests that, with global warming, forest fires frequency will increase all over the world. Moreover, several studies point that global warming is likely to increase fire frequency and severity worldwide [Flannigan and Van Wagner, 1991; Stocks *et al.*, 1998; Flannigan *et al.*, 1998; Wotton *et al.*, 1998; Flannigan *et al.*, 2000; Carvalho *et al.*, 2001; Williams *et al.*, 2001; Marques and

Rocha, 2003; Brown *et al*., 2004; Fried *et al*., 2004; Hennessy *et al*., 2005; Moreno *et al*., 2005; Moriondo *et al*., 2006]. Assessments of the potential impacts of climate change on fire weather risk in the forests of Canada and United States [Flannigan and Van Wagner, 1991; Stocks *et al*., 1998; Flannigan *et al*., 1998, 2000; Wotton *et al*., 1998] have used General Circulation Models (GCMs) outputs to project fire severity using, for example, components of the Canadian FWI System. Results have shown increasingly severe fire weather across most of the western boreal forest of Canada and United States. In addition to rises in seasonal means of fire severity indices, these studies also predict enhancements in the frequency of occurrence of extreme fire severity in specific areas [Wotton *et al*., 2003] and increase in the fire season length [Wotton and Flannigan, 1993].

Research with respect to climate simulation and prediction has attracted considerable efforts throughout the last 30 years with global aspects clearly dominating. However, it is the regional and the local climate that is of central importance to societies and to the biosphere [Grell *et al*., 2000]. The GCMs spatial resolution, which is still typically several hundred kilometres, is considered insufficient for many purposes namely for regional impact studies such as those on forest fires, especially in regions like the Mediterranean with a complex morphology [Giorgi, 1990]. This has given rise to the development of various downscalling methods that attempt to derive finer-scale information out of GCM simulations [Giorgi and Mearns, 1991]. One of these methodologies is dynamical downscalling, in which a high-resolution (typically 20–50 km) regional climate model (RCM) is run in a limited domain, using boundary conditions provided by a GCM simulation. In comparison with another commonly used set of methods – statistical downscalling [Wilby and Wigley, 1997], dynamical downscalling is physically based but also much more computationally expensive. RCMs have been developed since the 1970s, and are now used in a wide range of different applications. The main aim of RCMs in the context of climate change is to add valuable higher resolution details to GCM integrations but keep the large-scale features. Realistic details are expected both spatially and temporally.

The application of RCMs can represent an important step forward in order to better simulate the fine scale atmospheric features and to capture effects of regional forcing in areas of complex topography as Portugal. In addition, the country dimension and the sea-land interaction derived from its vicinity to the Atlantic Ocean requires higher resolution simulations and analysis.

In this scope, the main objective of this chapter is to assess the future impacts of climate change on the fire weather risk over Portugal derived from the regional climate model HIRHAM [Christensen *et al*., 1996] simulations. The impact of different spatial resolution climatic scenarios on fire weather risk will also be discussed.

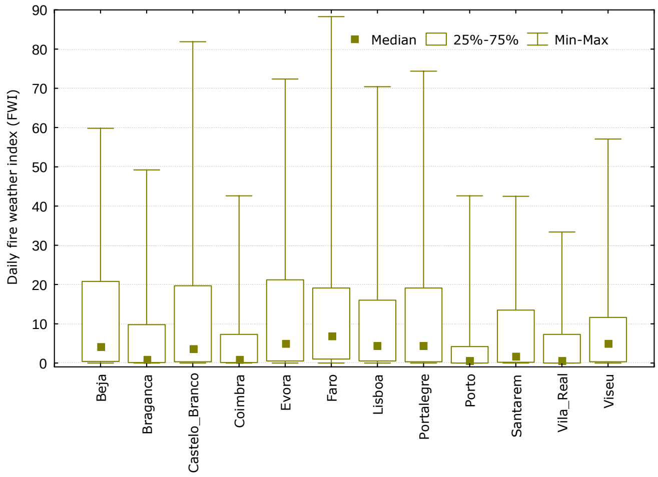
## 4.2. Data and Methods

Firstly, an overview of the fire severity data for the period between 1980 and 2005 that is used to validate the reference climate simulation is presented - *Observed fire weather risk between 1980 and 2005*. Secondly, the selected climatic scenarios and applied methodologies are described – *Regional climatic data description*.

### 4.2.1. Observed fire weather risk between 1980 and 2005

The fire weather data described and analysed in Chapter 3 was used in this section for the validation of the reference climate simulation over Portugal. Additionally, the year 2005 is also considered. A temporal and a spatial analysis of the FWI components is conducted in order to better characterize their main patterns and characteristics.

Concerning the fire weather risk, Figure 4.1 presents the daily mean fire weather index (FWI) from 1980 to 2005. Porto district exhibits the lowest values. The southern region formed by Portalegre, Évora, and Beja districts presents the highest interquartilic interval (interquartile range from 25$^{th}$ percentile to 75$^{th}$ percentile) of FWI values. In terms of yearly distribution, 2005 (Figure 4.1b) presents the highest interquartilic interval of values but the maximum FWI index was attained in 2004. According to the monthly distribution (Figure 4.1c), July presents the maximum FWI value but the interquartilic interval remains almost the same between July and August. As expected, the period between May and October presents the highest FWI values.

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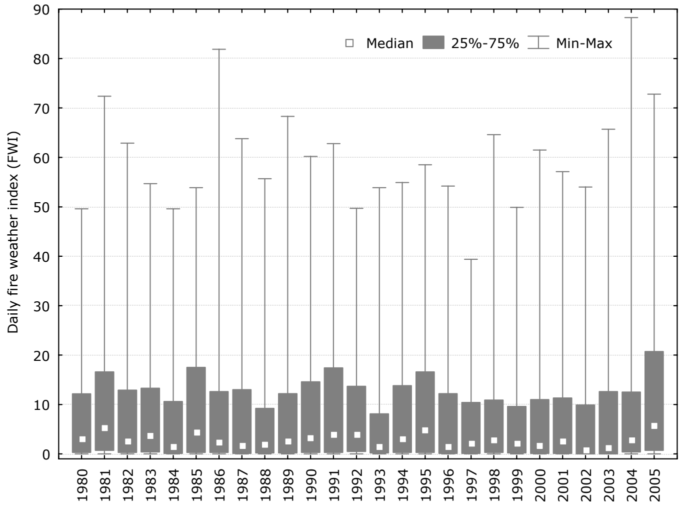


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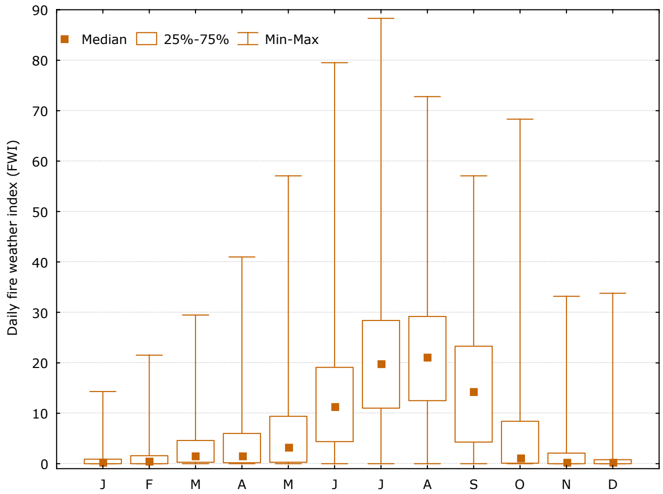



c)

Figure 4.1 – Daily fire weather index (FWI) between 1980 and 2005 by a) district, b) year and c) month.

The 12 stations fire weather data was used to estimate the FWI spatial distribution for Portugal. A Geographic Information System (GIS) software was used to compute a spline interpolation [Schumaker, 1981] over the monthly means of the FWI daily values estimated between 1980 and 2005. Figure 4.2 presents the FWI spatial distribution over Portugal, from May to October, between 1980 and 2005.

July and August register the highest values and the southern regions are also the main affected. The monthly mean FWI values range from 1 to 32 depending on the region giving an indication on the associated fire danger. According to Viegas *et al*. [2004] the highest FWI values registered in the southern region are associated to low fire danger classes (Table 3.2, pp 42). On the contrary, in July and August the districts of the centre and north interior present FWI values ranging from 13 to 29, which are related to moderate to high level of fire danger. The coastal regions in the north and Centre show the lowest FWI values ranging from 1 to 12. In these regions the obtained FWI values are related to a low to moderate level of fire danger.

The FWI index spatial distribution has a markedly NW-SE gradient. The NW region of Portugal exhibits the lowest FWI values and the SE the highest. This gradient is in agreement with the temperature patterns and the mean sea level pressure field of the summer climatology over the Iberian Peninsula discussed in Chapter 2 (Figure 2.4).

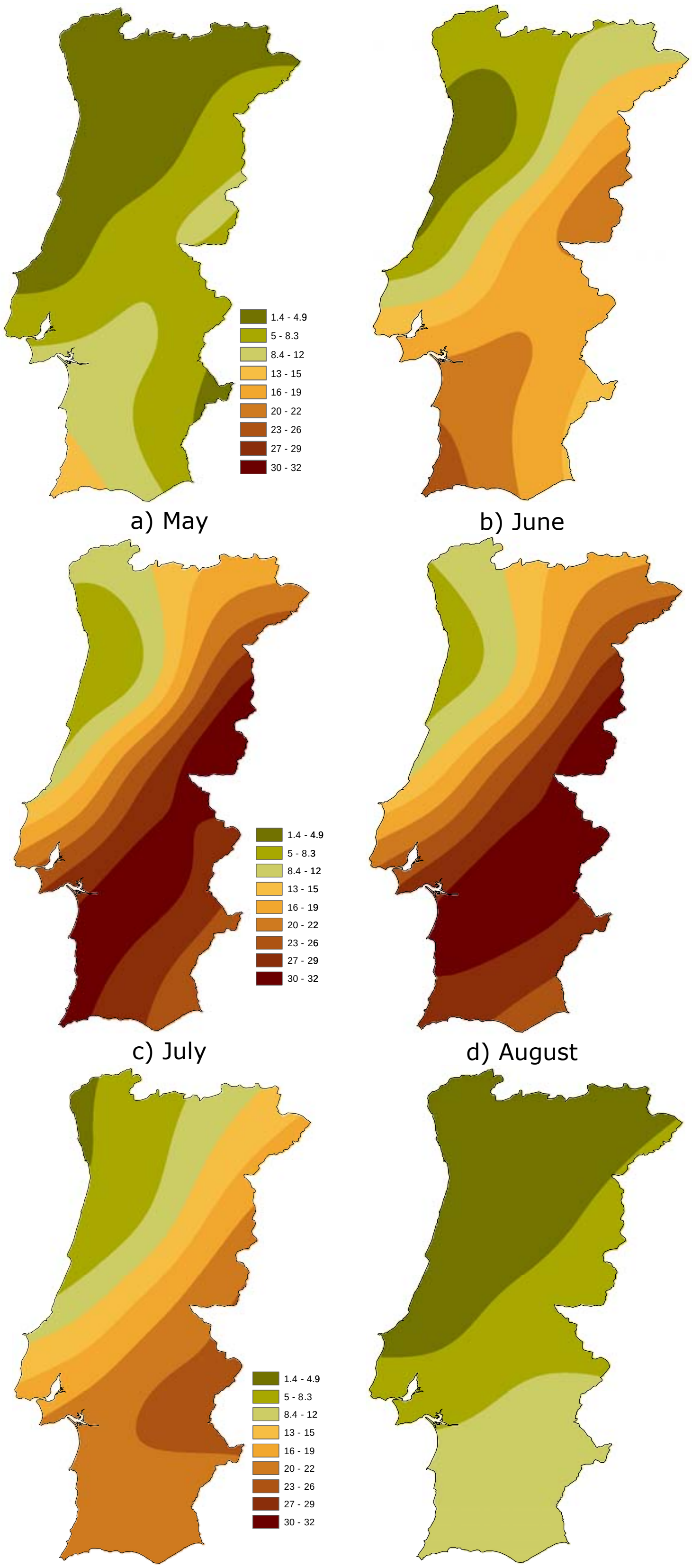



Figure 4.2 – Monthly mean fire weather index (FWI) between 1980 and 2005 for a) May, b) June, c) July, d) August, e) September, and f) October.

#### 4.2.2. Regional climatic data description

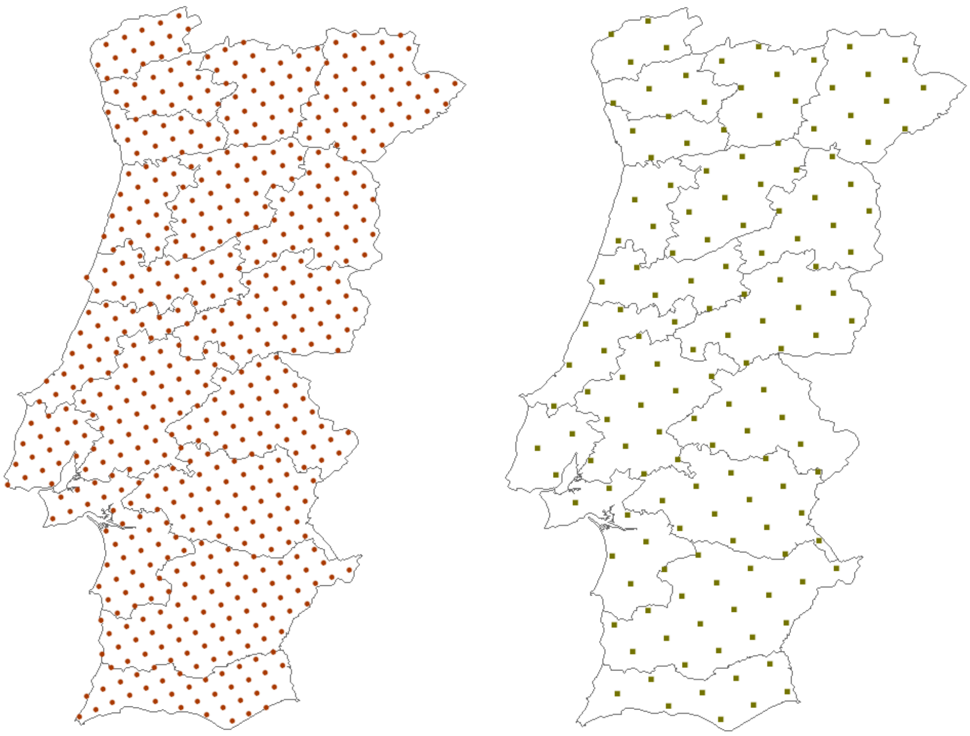
Daily climatic data were collected from the regional climate model HIRHAM [Christensen *et al*., 1996], at two spatial resolutions, 12 km and 25 km, from the **P**rediction of **R**egional scenarios and **U**ncertainties for **D**efining **E**uropea**N** **C**limate change risks and **E**ffects – PRUDENCE – project [PRUDENCE, 2005], considering the IPCC Special Report on Emissions Scenarios (SRES) A2 scenario [Nakicenovic *et al*., 2000]. The PRUDENCE simulations are freely available to be used for scientific research namely for impact assessment studies

The starting point for each SRES projection is a narrative ''storyline'', describing the way world population, economies and political structure may evolve over the next few decades. Four storylines were defined, and for each storyline several emissions scenarios were constructed, producing four ''scenario families''. Ultimately, six SRES marker scenarios were defined (one of the families has three marker scenarios, the others one each) – A1F1, A1T, A1B, A2, B1, B2 - and climate modellers agreed to use some or all of these six marker scenarios to drive their climate models to develop a series of comparable climatic scenarios. The SRES storylines provide more than just input drivers to climate models. They represent a diverse range of different development pathways for the world which provide a meaningful basis for impact estimates [Arnell *et al*., 2004]. The IPCC SRES A2 scenario is characterized by a very heterogeneous world with a continuously increasing global population. The economic development is primarily regionally oriented and *per capita* economic growth and technological change are more fragmented and slower than in other IPCC scenarios. In this sense, the A2 is considered a high emission scenario.

Within PRUDENCE four different Atmospheric General Circulation Models (AGCMs) and ten different Regional Climate Models (RCMs) were applied to get an estimate of the uncertainty for reference (1961-1990) and future (2071-2100) climatic scenario derived by the different model formulations. The same observed time series of sea surface temperatures (SSTs) and emissions of trace gases and sulphate aerosols were used to drive the models. For future climate the sea surface conditions as predicted from state of the art Atmosphere Ocean General Circulation Models (AOGCMs) and the changes in the radiative forcing derived from the SRES A2 were used [Christensen and Christensen, 2007]. The HadAM3H model [Buonomo *et al*., 2007] was chosen to be the central GCM delivering lateral boundary conditions to the RCMs used for the PRUDENCE ensemble. The RCMs used their own model setup as well as grid specifications like number of vertical levels. However, similar horizontal resolutions of about 50 km were considered with the exception of the HIRHAM model that also presented simulations at 25 km and 12 km.

The HIRHAM4 [Christensen *et al*., 1996] was the applied model version within the PRUDENCE simulations. The dynamical part of the model is based on the hydrostatic limited area model HIRLAM [Källén, 1996]. Prognostic equations exist for the horizontal wind components, temperature, specific humidity, liquid water content and surface pressure. HIRHAM4 uses the physical parameterisation package of the general circulation model ECHAM4 [Roeckner *et al*., 1996]. These parameterisations include radiation, land surface processes, sea surface sea-ice processes, planetary boundary layer, gravity wave drag, cumulus convection and stratiform clouds.

In order to assess the influence of spatial resolution on the fire weather risk and subsequently on forest fire activity over Portugal the HIRHAM highest resolution climate change simulations, at 25 km and 12 km, were selected (Figure 4.3).



a) b)

Figure 4.3 – HIRHAM grid cells over Portugal at a) 12 km resolution and b) 25 km resolution.

As fire weather is strongly influenced by the meteorological variables behaviour, a detailed validation was performed over Portugal applying the non-parametric statistical test – Wilcoxon Score Test [van Elteren, 1960] at the selected 12 meteorological stations between 1980 and 1990 (11 year period for which observed data were available). Figure 4.4 presents the meteorological stations location used in the validation procedure (the same meteorological stations presented in Table 3.1, pp 39). Unfortunately, it was not possible to validate the full 30 year (1961 – 1990) simulated values due to lack of data. Using SAS version 9.1.3 monthly mean values of the simulated daily mean temperature, daily maximum temperature, daily mean wind speed, total precipitation, and daily mean relative humidity and fire weather risk variables were evaluated.

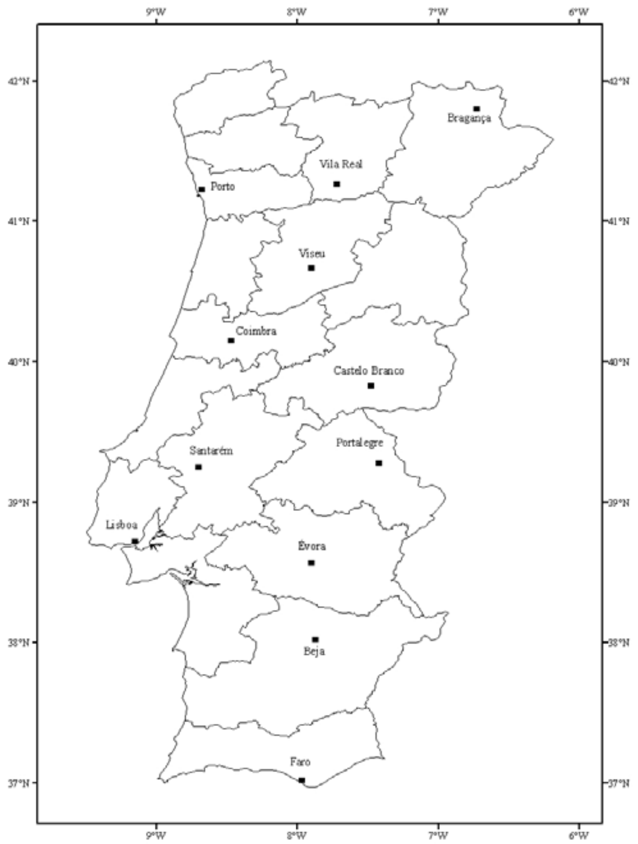



Figure 4.4 - Portuguese meteorological stations used for the reference scenario analysis.

## 4.3. Results and Discussion

In this section the reference regional climate simulations are validated - *Reference climatic scenario (1961-1990) analysis*, and the impacts of climate change on the fire weather risk are assessed for two spatial resolutions (12 km and 25 km) – *Climate change impacts on fire weather risk*.

#### 4.3.1. Reference climatic scenario (1961-1990) analysis

In the scope of PRUDENCE project all the models have been evaluated for the reference climate simulation. According to Jacob *et al*. [2007], the HIRHAM model presents a slightly warm bias in winter and summer over the Iberian Peninsula that decreases with higher spatial resolution. The ensemble mean of all RCMs applied within PRUDENCE project presents a slightly cold bias in winter (-0.19) and a warm bias in summer (0.48). For precipitation, HIRHAM exhibits a dry bias in winter that decreases with resolution and a wet bias in summer that increases with resolution. Over the Iberian Peninsula, the ensemble mean presents a dryer tendency in summer (-0.02) and in winter (-0.43). The interannual variability of temperature and precipitation revealed by HIRHAM model for both simulations is very close to the Climatic Research Unit – CRU [New *et al*., 2002] dataset [Jacob *et al*., 2007].

To better assess the impact of climate change on forest fire risk over Portugal a more detailed analysis of the HIRHAM reference simulation was performed. Hence, the Wilcoxon score test was applied to the monthly means of the daily values of the meteorological variables and to the FWI System components between 1980 and 1990.

Figure 4.5 shows the monthly mean of daily average temperature distribution from 1980 to 1990 for the analysed stations. The monthly mean of daily average temperature is well simulated by the model at 12 km and 25 km resolution (Figure 4.5). The non-parametric test reveals that at 12 km resolution there are no significant differences between the observed and the modelled temperature at a 0.05 significance level except for the southern stations of Évora, Beja and Faro. In average, in this part of the country, there is an overestimation of mean temperature of approximately + 2 ºC. Faro station exhibits an overestimation of + 1.3 ºC. The HIRHAM mean temperature outputs at 25 km present a good agreement with the observed values. According to Flannigan *et al.* [2002] this difference is inside the accepted range (± 3 °C) for fire weather impact assessment studies.

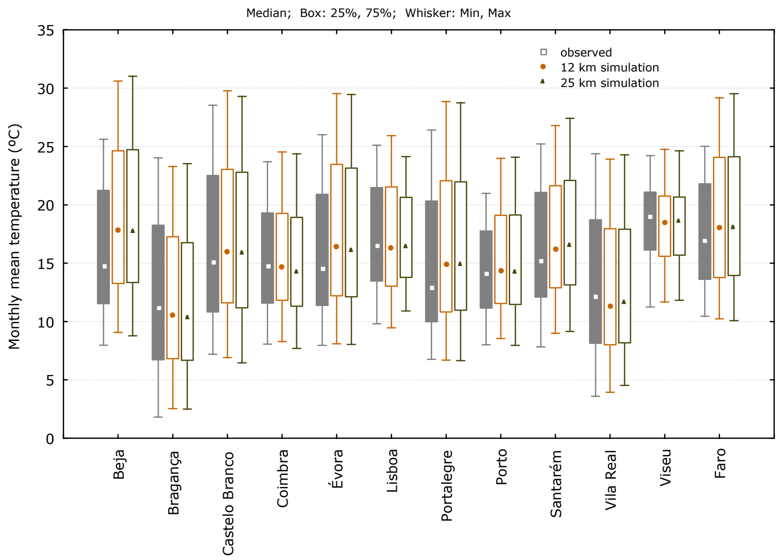



Figure 4.5 - Monthly mean of daily average temperature (ºC), by station, for the 1980-1990 period, for observed data (grey boxes), HIRHAM 12 km simulation (orange boxes) and HIRHAM 25 km simulation (dark green boxes).

Regarding wind speed, HIRHAM outputs, for both simulations, are inside the acceptable range (± 3 km $h^{-1}$) for this type of study [Flannigan *et al.*, 2002]. Although in Santarém, Vila Real, and Viseu stations the obtained values are overestimated. Wind speed can be dependent on very small scale variations in surface topography and such is hard to model [Wotton *et al.*, 1998].

Humidity plays an important role in fire danger. Low humidity days are necessary for drying fine fuels which carry the fire [Wotton *et al.*, 1998]. The outputs of the HIRHAM model do not consider relative humidity or even specific humidity; instead dew point temperature is available.

The relative humidity (RH) was computed based on the relationship established in equation 4.1:

$$\frac{\mathrm{RH}}{100} = \frac{e}{e_s} \qquad (4.1)$$

where $e_s$ is the saturation vapour pressure given by a specific derivation of the Clausius-Clapeyron equation that describes the dependence of saturated water vapor pressure on temperature (Equation 4.2)

$$e_s = e_0 * \exp\left[\frac{L}{R_v} * \left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \qquad (4.2)$$

where $e_0$ is the reference saturation vapor pressure at $T_0 = 273.15K$ (611.2 Pa); $L$ is the latent heat of evaporation (2.453x10$^6$ J kg$^{-1}$); $R_v$ is the water vapor gas constant (461 J K$^{-1}$ kg$^{-1}$); $T_0$ is the reference temperature (273.15 K) and $T$ the actual temperature (K). In equation 4.1, $e$ represents the water vapour pressure and is also estimated through equation 4.2 but instead of $T$ the dew point temperature must be used ($T_{dew}$).

At 12 km resolution, the computed relative humidity (RH) presented significant differences against the observed data. The maximum differences in relative humidity were registered in the south namely at Faro (-15.5 %), Beja (-15 %), Évora (-11.5 %) and also at Santarém (-10 %). According to Flannigan *et al.* [2002], for climate change impact studies on forest fire activity, the relative humidity acceptable range should be ± 5%. The HIRHAM control simulation does not satisfy this criterion and considering that the fire weather is highly influenced by the humidity in the atmosphere it was decided to evaluate how well the model predicts the dew point temperature (hereafter denoted as Tdew).

Comparing the simulated Tdew with the observed values, at each weather station, it was detected that HIRHAM presents a cold bias. The highest differences detected were in the south of the country and in autumn (not shown). From this analysis it was decided to correct the Tdew simulated values in order to estimate a more reliable relative humidity field over Portugal. It was not considered any spatial adjustment (based on stations location) but only a temporal (monthly) discrimination. It was concluded that, from January to September and December, the Tdew presents a difference of 1ºC and for October and November it registers a 2.5 ºC difference.

At 25 km resolution the relative humidity, and especially for the southern part of the country, also presented lower values than the measured data although the differences were not so pronounced as for the 12 km simulation. The relative humidity differences reached -14 % in Faro, -13 % in Beja, -9 % in Santarém and -8 % in Évora. A detailed analysis of the dew point temperature simulated by the HIRHAM at 25 km also detected a cold bias comparatively to the stations observed values. This bias was also corrected on a monthly basis because October and November exhibited the highest differences. The dew point temperature was corrected with +0.5 °C in all months except in October and November where a +2 °C correction was considered. The obtained correction factors for the dew point temperature were applied to the reference simulation and also to the future climate simulation at both analyzed spatial resolutions.

After the Tdew correction, for both simulated resolutions, the relative humidity field of the reference simulation was re-estimated and re-evaluated. The updated statistical test indicated that the RH values were closer to the observed ones. In the south dryer values than the observed data still remain, but the obtained differences are within the acceptable range for this type of study except in Beja and Faro stations. In Porto, Lisboa, Santarém and Évora significant statistical differences can be detected between estimated and observed mean relative humidity values but these differences are inside the ± 5 % acceptable range (Figure 4.6). According to Figure 4.6, the interquartilic range of the RH values tends to be similar in both reference simulations except in Lisboa and Viseu stations. Although, there is a clear underestimation of the interquartilic range in Faro, Beja, Porto, and Santarém stations.

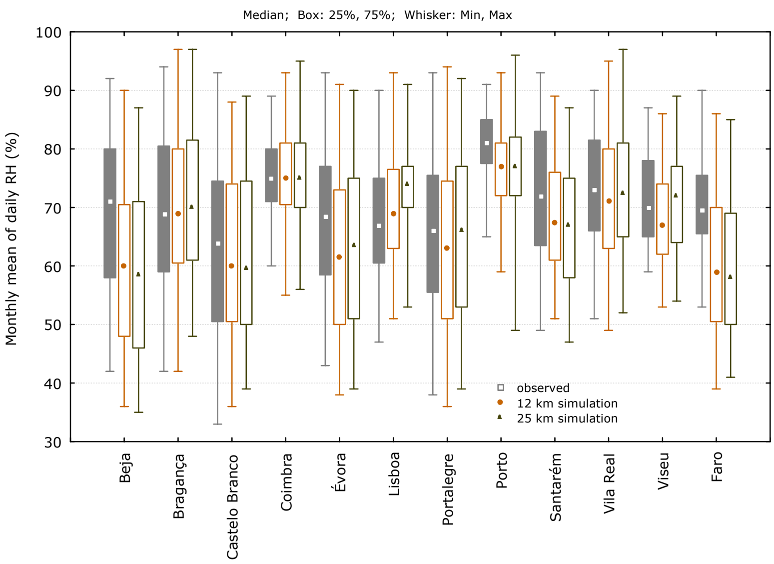



Figure 4.6 - Monthly mean of daily relative humidity – RH (%) for 1980-1990 period, for observed data (grey boxes), HIRHAM 12 km simulation (orange boxes) and HIRHAM 25 km simulation (dark green boxes) by station.

Concerning precipitation, the HIRHAM at 25 km resolution presents a wet bias in the south of the country. The model exhibited high frequency in the small rainfall events as detected in Wotton *et al.* [1998]. The districts of Évora, Beja, Lisboa, and Santarém show higher precipitation daily amounts. In the north, Bragança also exhibits higher daily rainfall amounts. These differences are statistically significant. A constant correction factor applied to the simulated daily precipitation values is an adequate calibration procedure [Mearns *et al.*, 1995; Flannigan *et al.*, 2005a]. This type of correction has been applied on modelled rainfall data in other studies [Bergeron and Flannigan, 1995; Beer and Williams, 1995; Wotton *et al.*, 1998]. Since the forest fire activity is highly dependent on the precipitation regimes [Viegas *et al*.; 1992; Viegas and Viegas, 1994] the precipitation amounts frequency and the frequency of duration of rain-free periods was assessed for the 25 km reference simulation. Several correction values were tested in order to set the simulated precipitation frequencies as close as possible to observed ones. The correction factor for the precipitation amount that revealed more adequate for the south part of Portugal was 1.5 mm (Figure 4.7). This correction factor was applied between latitudes 37.5 ºN and 39.5 ºN (Figure 4.4) to the reference simulation and also to the future climatic scenario simulation at 25 km resolution. Figure 4.7 exhibits the daily rainfall amount frequencies in Santarém, Lisboa, Évora, and Beja. The precipitation correction applied over the 25 km resolution conducted to a better representation of the southern region precipitation amounts frequency (Figure 4.7 and Figure 4.9). Due to its local behaviour, no correction factor was applied in Bragança.

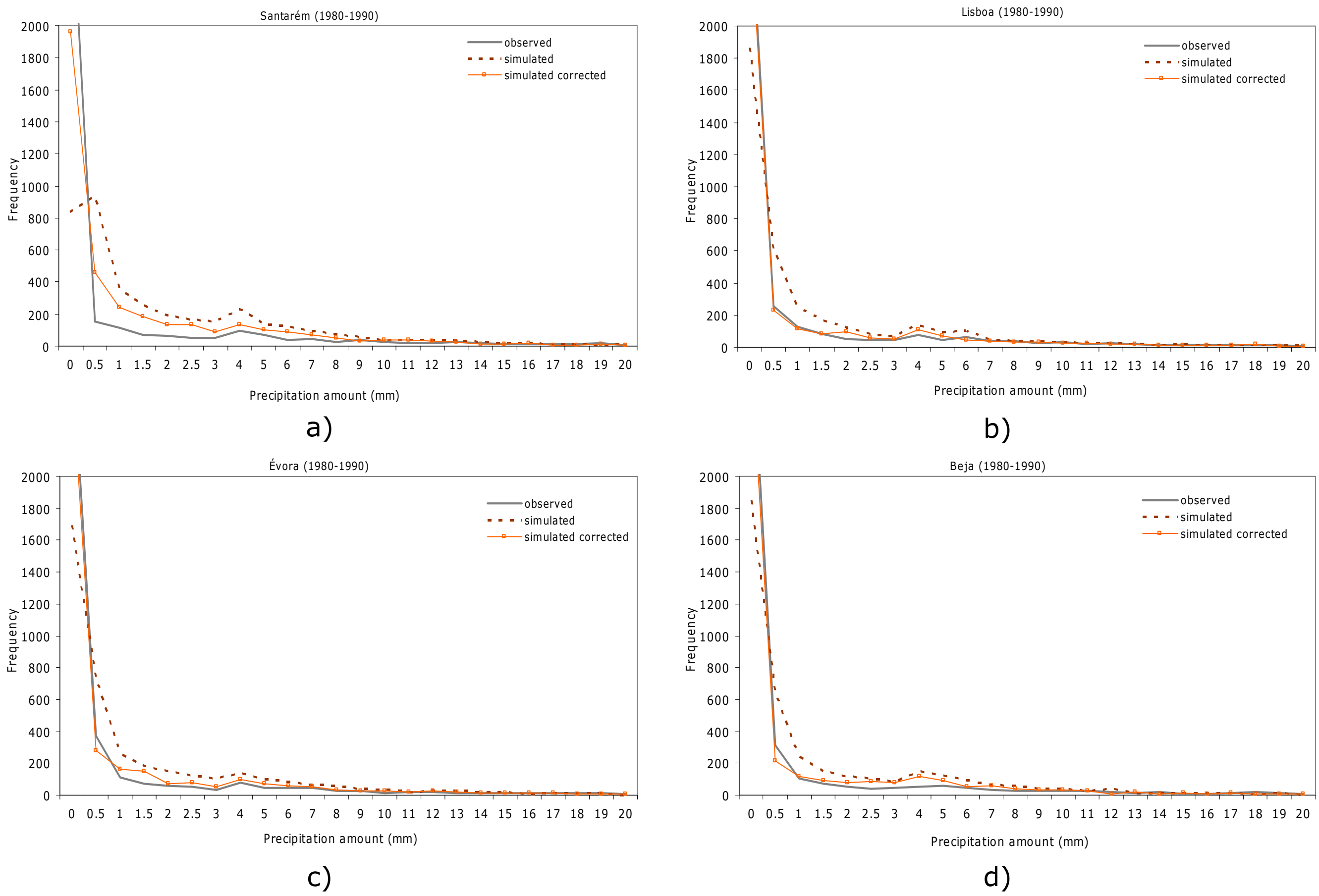



Figure 4.7 - Daily rainfall amount frequencies at four Portuguese southern stations, (a) Santarém, (b) Lisboa, (c) Évora, and (d) Beja. The solid line represents the observed daily precipitation data for the period 1980-1990. The dashed line represents the uncorrected frequencies from the HIRHAM 25 km simulation. The line with squares represents the frequencies from the HIRHAM after the correction (-1.5 mm) was applied.

As stated previously, the frequency of duration of rain-free periods was also analysed (Figure 4.8). There is a clear improvement of the dry spell length after the precipitation amount correction in the 25 km simulation. In Santarém station this is not so obvious, which could be closely related to local features that are influencing the precipitation distribution in the region. In Lisboa, Évora, and Beja the dry spell length is clearly improved diminishing the frequency of 1 to 4 consecutive days without any rain.

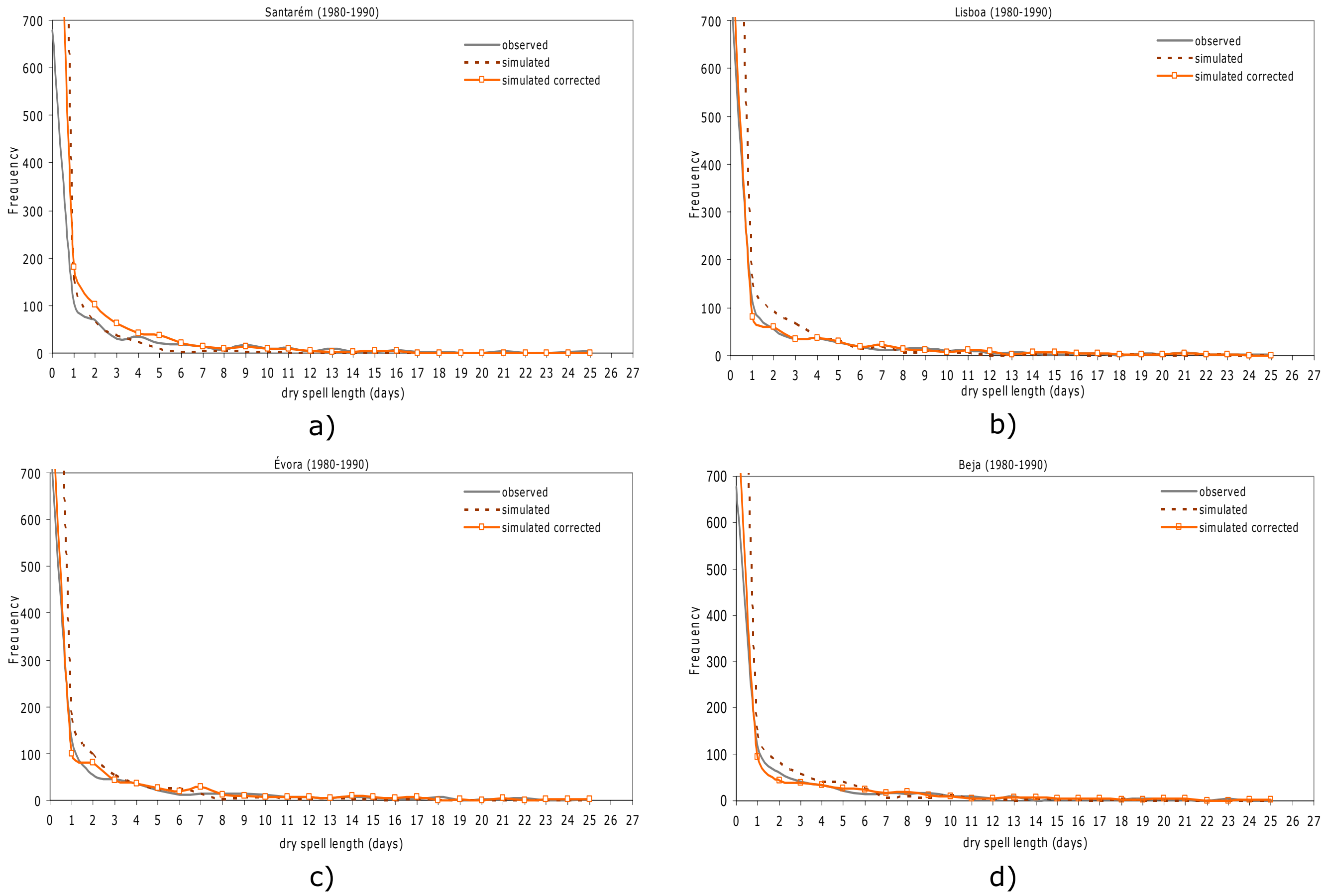



Figure 4.8 - Dry spell length frequencies at four Portuguese southern stations, (a) Santarém, (b) Lisboa, (c) Évora and (d) Beja. The solid line represents the observed dry spell length for the period 1980-1990. The dashed line represents the uncorrected frequencies from the HIRHAM 25 km simulation. The line with squares represents the frequencies from the HIRHAM after the correction (-1.5 mm) was applied.

At 12 km resolution, monthly precipitation presents a good agreement with measured data except in Bragança, where the difference in the monthly totals is statistically significant. The monthly mean of the daily precipitation is only statistically different in Bragança. According to Figure 4.9 the reference simulation at 12 km and at 25 km resolution (after daily precipitation correction) exhibits a reasonable agreement with the observed precipitation values except in Bragança. It should be stated that in some stations (Coimbra, Lisboa, Portalegre, and Porto) the simulations present higher maximum values than the observed ones. For Viseu station the median of monthly mean of daily precipitation is very close to the observed value although the interquartilic range is clearly underestimated.

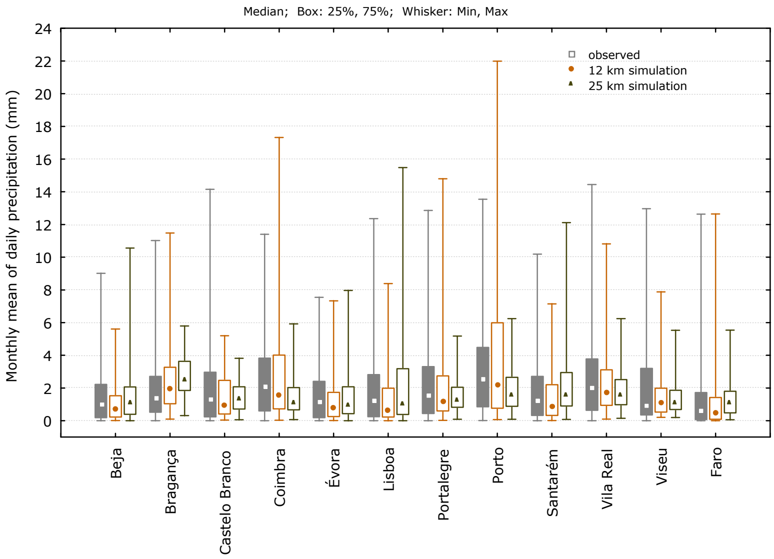



Figure 4.9 - Monthly mean of daily precipitation (mm) between 1980 and 1990, for observed data (grey boxes), HIRHAM 12 km simulation (orange boxes) and HIRHAM 25 km simulation (dark green boxes) by station.

The previously analysed variables (temperature, wind speed, relative humidity, and precipitation) were used to estimate the Canadian FWI System components - FFMC, DMC, DC, BUI, ISI and the FWI (see Figure 3.5, pp 40). Based on the Wilcoxon score test results the FWI System components presented a good agreement with the observed values at the majority of the analyzed stations. At 12 km resolution the DC component exhibits statistically significant differences in Portalegre, Santarém, Lisboa, Évora, Beja and Vila Real. The FWI index is only significantly different in Santarém and Beja stations. The HIRHAM 25 km reference simulation exhibits good agreement between the simulated and observed FWI components. The differences are only significantly different for DC in Porto, Vila Real, Coimbra, Portalegre and Évora. The FWI significant differences can be detected in Bragança, Santarém and Beja. The FFMC presents significant differences in Lisboa, Bragança and Vila Real. Figure 4.10 and Figure 4.11 show the FFMC and the FWI components at 12 km and 25 km resolution and the observed data. Only Bragança station exhibits a different behaviour from the observed FFMC values (Figure 4.10).

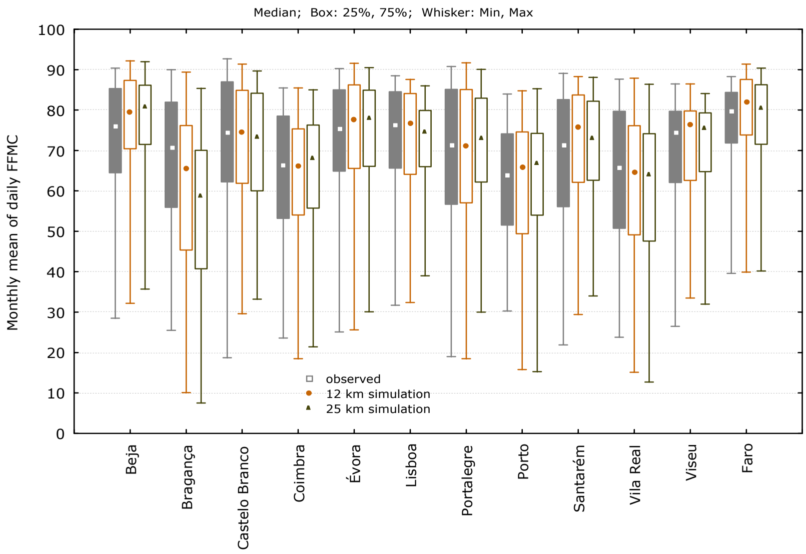



Figure 4.10 - Monthly mean of daily Fine Fuel Moisture Code (FFMC), between 1980 and 1990, for observed data (grey boxes), HIRHAM 12 km simulation (orange boxes) and HIRHAM 25 km simulation (dark green boxes), by station.

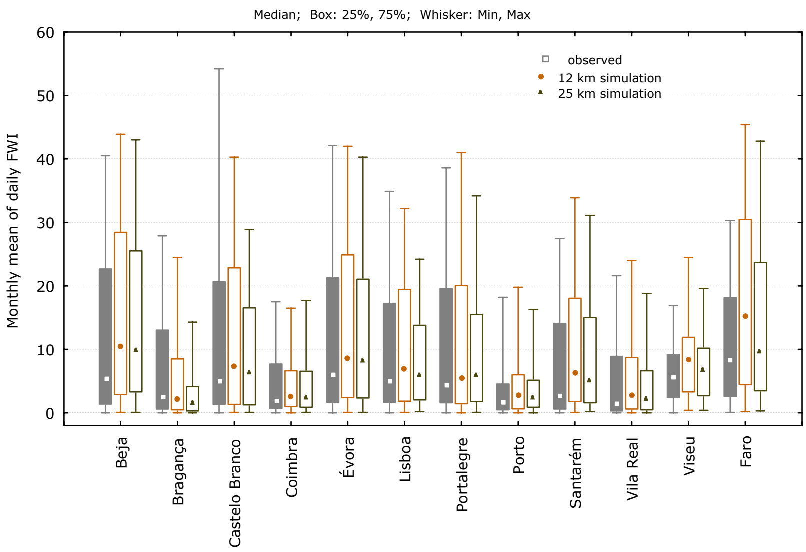
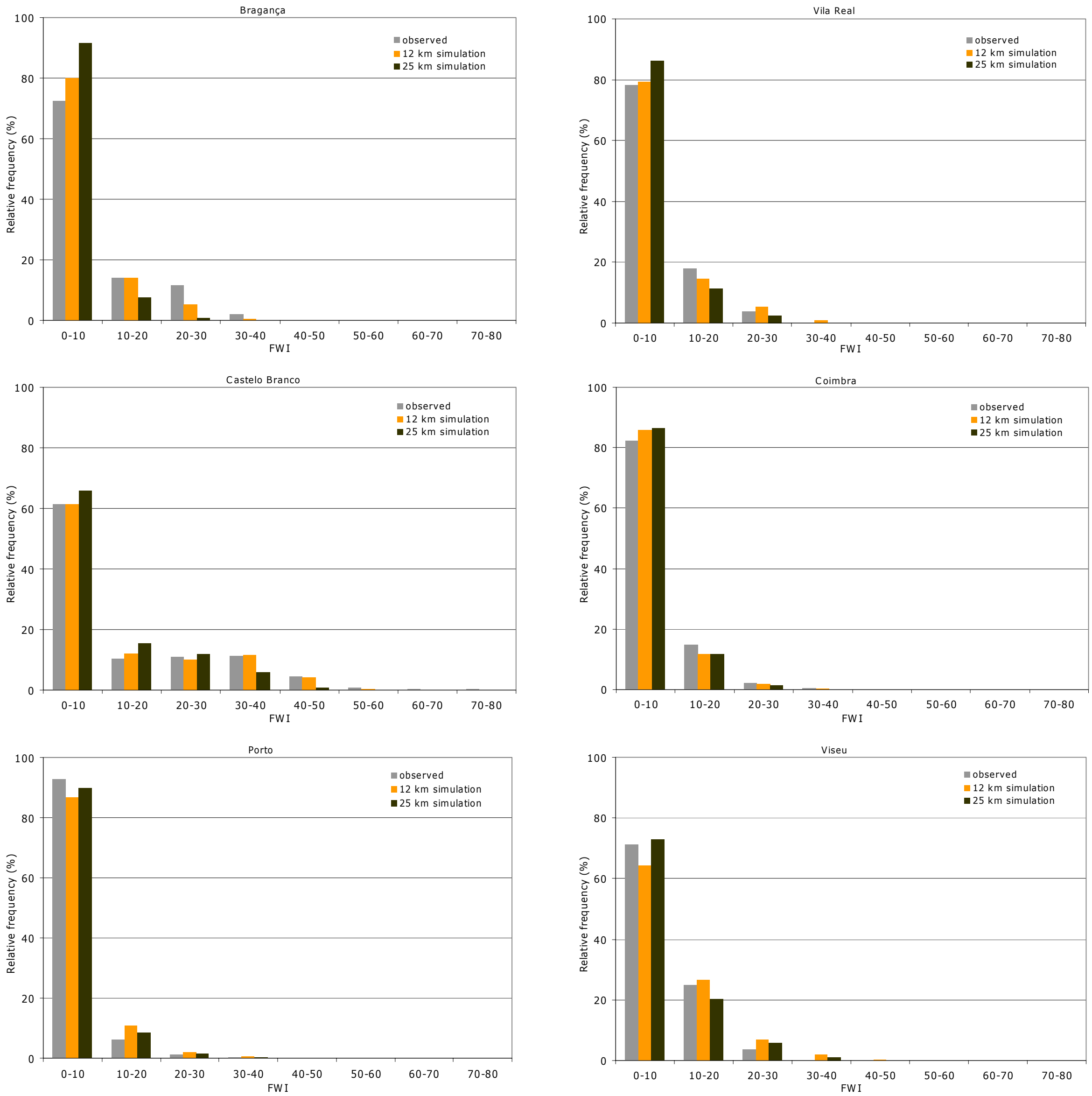



Figure 4.11 - Monthly mean of daily Fire Weather Index (FWI), between 1980-1990, for observed data (grey boxes), HIRHAM 12 km simulation (orange boxes) and HIRHAM 25 km simulation (dark green boxes), by station.

The FWI values are also correctly simulated by HIRHAM model except in Beja station where the median is clearly overestimated (Figure 4.11). Faro station also exhibits an overestimation of the FWI component at 12 km resolution. Results at this resolution tend to show higher maximum values than the 25 km resolution HIRHAM simulation for both analysed variables. According to Figure 4.11, HIRHAM 12 km simulation tends to present higher simulated FWI values for the 75th percentile except in Bragança, Coimbra and Vila Real stations. The 25th percentile presents reasonable values in both simulations except in Beja and Santarém stations. The poor results obtained for FFMC and FWI variables in Bragança station, especially in the 25 km simulation, can be at some extent, related to the overestimation of precipitation in this region.

Figure 4.12 shows the mean daily FWI component relative frequencies between 1980 and 1990 for observed and simulated values. It should be remembered that Viseu only has data between 1982 and 1990, and from May to October, and for Castelo Branco available data corresponds to the 1985-1990 period (Table 3.1, pp 39). The FWI frequency classes were selected based on the analysis of Viegas *et al*. [2004].



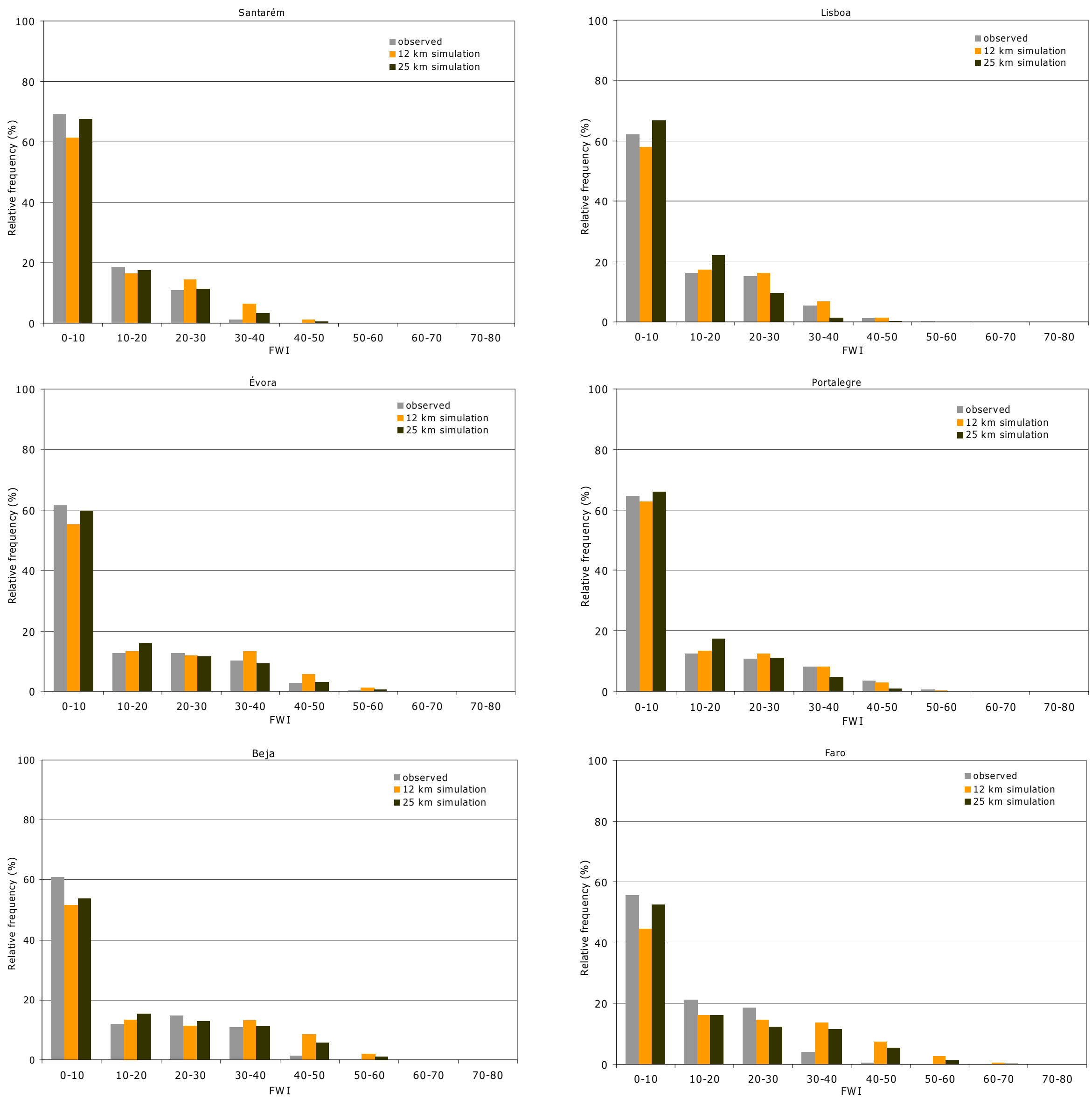



Figure 4.12 - Relative frequencies between observed and simulated (at 12 km and 25 km) mean daily FWI, for the 12 analysed districts between 1980 and 1990.

For Bragança the simulations overestimate the first class (0-10) and underestimates the 20-30 and 30-40 classes of the FWI values. This is closely related to the weak performance of the HIRHAM model at this weather station. The remaining stations exhibit a good frequency of distribution of the analysed FWI classes although there is a tendency to overestimate the frequency of values above 30, in both simulations, in Viseu, Santarém, Beja, and Faro. For the 0-10 FWI class the 25 km simulation presents better results than the 12 km simulation except in Castelo Branco, Vila Real, and Lisboa. From the validation point of view, it is important that the model produces a good distribution of the FWI frequency classes because these are clearly related to fire danger in the different Portuguese districts [Viegas *et al*., 2004] and consequently these constitute an important tool to correctly assess fire weather severity.

Table 4.1 and Table 4.2 summarize the validation procedure carried out at 12 km and 25 km resolution between 1980 and 1990 and the obtained statistical significant differences.

Table 4.1 – Statistical significant differences (x) obtained at 12 km resolution by district.

| | T | wind | RH | rain | FFMC | DMC | DC | ISI | BUI | FWI |
|---|---|---|---|---|---|---|---|---|---|---|
| Bragança | | | | x | x | | | | | |
| Vila Real | | x | | | | | x | | | |
| Porto | | | x | | | | | | | |
| Viseu | | x | | | | | | | | |
| Castelo Branco | | | | | | | | | | |
| Coimbra | | | | | | | | | | |
| Portalegre | | | | | | | x | | | |
| Santarém | | x | x | | | | x | | | x |
| Lisboa | | | x | | | | x | | | |
| Évora | x | | x | | | | x | | | |
| Beja | x | | x | | x | x | x | x | x | x |
| Faro | x | | x | | | | | | | |

Table 4.2 – Statistical significant differences (x) obtained at 25 km resolution by district.

| | T | wind | RH | rain | FFMC | DMC | DC | ISI | BUI | FWI |
|---|---|---|---|---|---|---|---|---|---|---|
| Bragança | | | | x | x | | | | | x |
| Vila Real | | x | | | x | | x | | | |
| Porto | | | x | | | | x | | | |
| Viseu | | | | | | | | | | |
| Castelo Branco | | | | | | | | | | |
| Coimbra | | | | | | | x | | | |
| Portalegre | | | | | | | x | | | |
| Santarém | x | x | x | x | | | | | | x |
| Lisboa | | | x | x | x | | | | | |
| Évora | x | | x | x | | | x | | | |
| Beja | x | | x | x | | | | | | x |
| Faro | x | | x | | | | | | | |

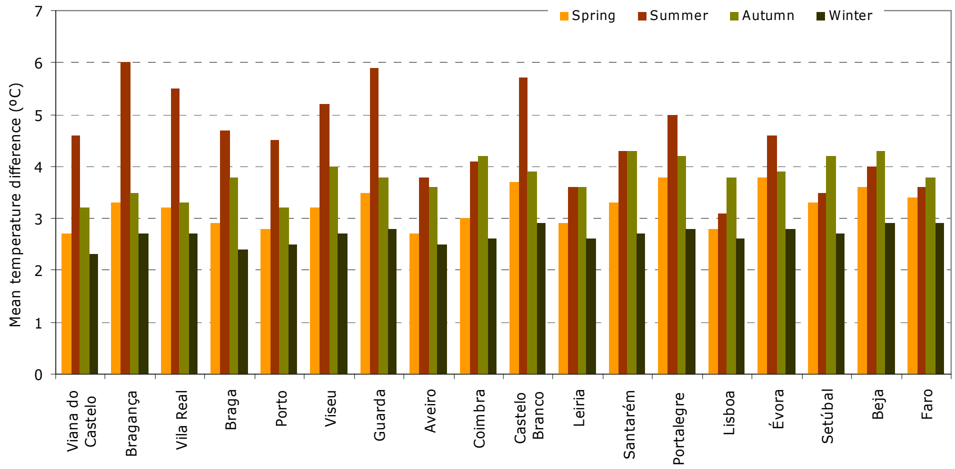
According to Table 4.1 and Table 4.2 the southern part of the country exhibits the worst results in terms of validation namely for the mean temperature and the relative humidity. The daily precipitation also shows significant statistical differences in the south at 25 km resolution. Within the FWI system components the DC is the most affected variable presenting statistical significant differences at 12 km and at 25 km resolutions. Even considering the limitations revealed by the validation procedure it is possible to conclude that the HIRHAM model simulations can be used to assess future forest fire weather risk over Portugal.

### 4.3.2. Climate change impacts on fire weather risk

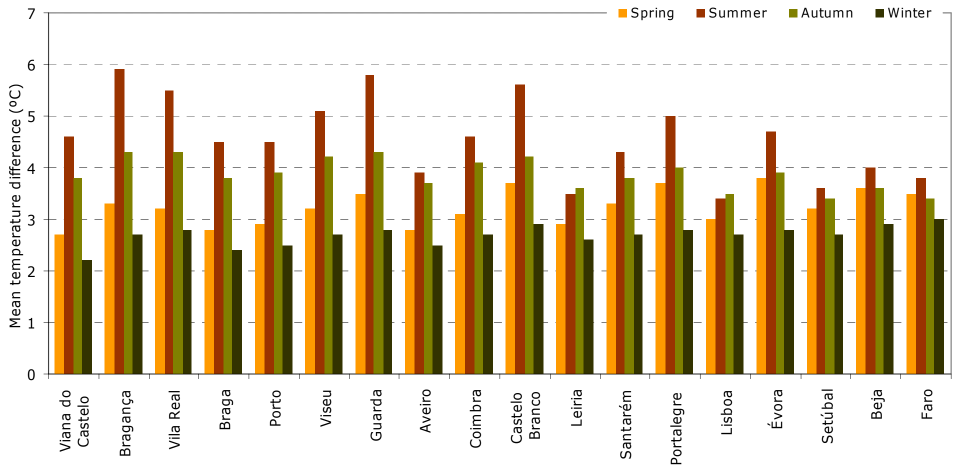
According to Christensen and Christensen [2007] all models within PRUDENCE project agree that the largest warming is projected to occur in the Mediterranean region, and most of the models point towards southern France and the Iberian Peninsula as the region most severely hit by a warming of more than 6 ºC. According to the authors HIRHAM model is in the middle of the range for most areas, fields and seasons, with a lesser projected drying during summer than average. It also has a slight tendency to less warming and a more positive precipitation change (in particular in summer season) with increased resolution. It is also stated that higher resolution of course gives higher topographic detail in the modelled fields. But it is also seen a tendency for less warming in the present model results. For HIRHAM model this is also connected to a marginally lower atmospheric humidity in the high resolution simulations and hence a lower greenhouse effect. Over the Iberian Peninsula HIRHAM model projects its highest warming in summer reaching 5.38 ºC in the 50 km resolution and 5.19 ºC in the 12 km simulation. The ensemble mean temperature increase for this region is 5.41 ºC. Concerning precipitation, all seasons will experience a decrease on the rainfall amounts but this will be more pronounced in summer, which already is the driest season of the year. The ensemble mean points to a decrease of 0.48 mm. In summer, the HIRHAM 50 km simulation projects a decrease of 0.39 mm and 0.36 mm reduction in the 12 km simulation [Christensen and Christensen, 2007].

To evaluate the impacts of climate change on the fire weather risk over Portugal a more detailed analysis was performed. The Wilcoxon score test was applied in order to better assess the differences between future and reference scenario. The statistical test was also applied in order to evaluate the projections derived from the 12 km and 25 km HIRHAM simulations. All results are statistically significant at a 95 % confidence interval. As has been stated previously, for the analysed time slices the IPCC SRES A2 is consistent to a 2 x $CO_2$ climatic scenario.

Figure 4.13 and Figure 4.14 show the impacts of a 2 x $CO_2$ climatic scenario on mean temperature and mean daily precipitation for both analysed resolutions.




a)

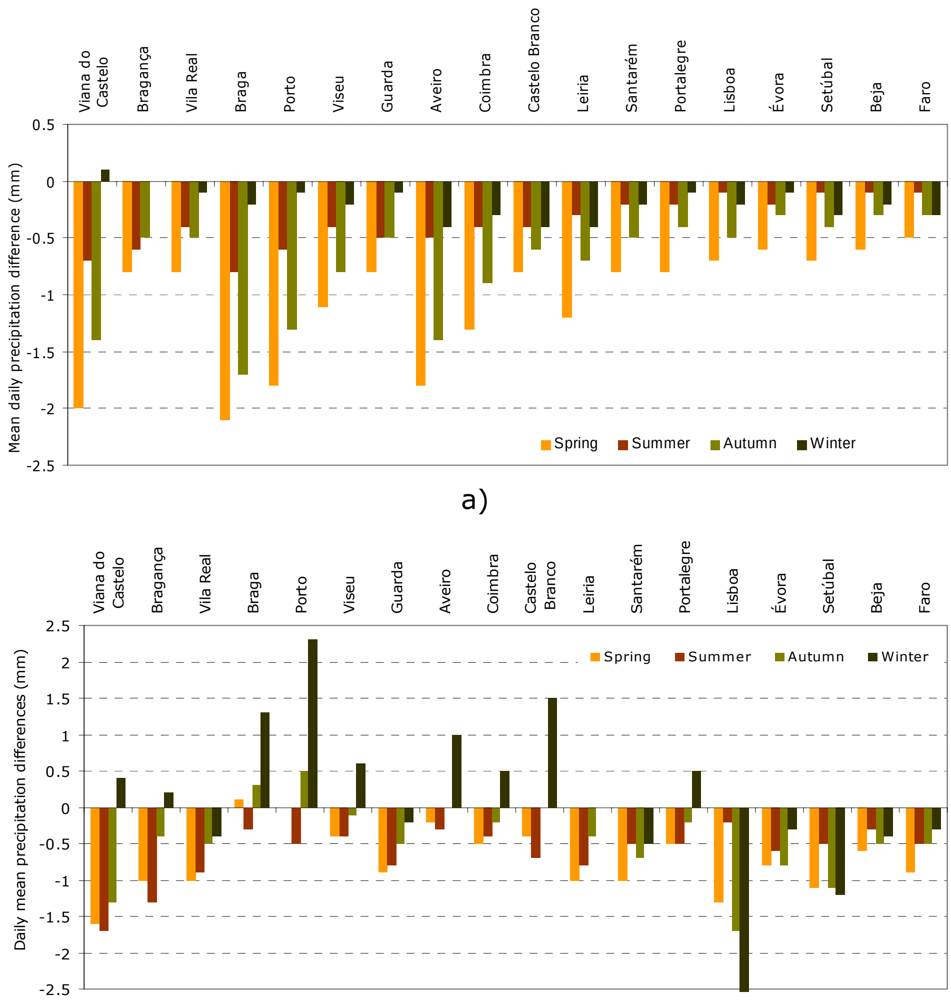



b)

Figure 4.13 – Mean temperature difference between future (2071-2100) and reference (1961-1990) climatic scenarios for a) 12 km and b) 25 km simulation, by season.

The HIRHAM projections at 12 km and at 25 km resolution over Portugal point to an increase of the mean temperature in all seasons especially in summer, reaching almost 6 ºC in the inner districts of Bragança, Guarda, and Castelo Branco ($p<0.0001$). The north and central part of the country will register the highest increases and the districts of Bragança, Vila Real, Viseu, Guarda, and Castelo Branco will be the most affected ones (Figure 4.13). Differences between both resolutions are more noticeable for the mean temperature in autumn where the 25 km simulation gives higher increase values for the north/centre districts and the 12 km simulations for the southern districts.

At 12 km resolution, the daily precipitation (Figure 4.14a) decreases in all seasons except in winter in Viana do Castelo district, although this increase is not statistically significant. Spring season is the most affected in precipitation reduction reaching almost -2.2 mm in Braga district (p=0.0009). The north and central part of Portugal registered the highest reductions in rainfall amounts.




b)
Figure 4.14 - Mean daily precipitation difference between future (2071-2100) and reference (1961-1990) climatic scenarios for a) 12 km and b) 25 km simulation, by season.

At 25 km resolution (Figure 4.14b) all seasons exhibit daily precipitation reductions except the districts of Braga, Porto, Viseu, Aveiro, Coimbra, and Castelo Branco in winter. This increase in winter precipitation is statistically significant. The reduction detected in spring precipitation in northern and centre districts at 25 km scenario is not as high as the 12 km precipitation decreasing. In summer the precipitation reduction is higher in the 25 km simulation. On the other hand, autumn exhibits higher rainfall amount decreases in the 12 km simulation. Actually, the southern districts already have lower precipitation rates than the northern and by the end of the XXI century in a 2 x $CO_2$ scenario a decrease is also projected. According to Viegas *et al*. [1992] and Viegas and Viegas [1994] winter and spring precipitation deeply influence the forest fire activity during summer. The projected increase in winter precipitation may contribute to the under-canopy vegetation development and to its accumulation for the next fire season. Additionally, the projectd daily rainfall reductions in spring may contribute to the drying of the vegetation leading to the enhancement of the fire risk over a region. These projections will deeply influence the fire weather risk patterns in future climate.

At a 0.05 significant level most of the projected variables revealed not to be significantly different between the 12 km and the 25 km simulation. The mean and the maximum temperature increments and the relative humidity decreases projected, by district, under future climate in both datasets are not statistically different. All the districts exhibit statistically significant differences in precipitation projections between both simulations except Beja, Viana do Castelo, Bragança, Vila Real, Leiria, Portalegre and Guarda.

The fuel moisture conditions are strongly influenced in future climatic scenario. The fine fuel moisture code (FFMC) increases and this is slightly higher in the 25 km simulation (Figure 4.15).

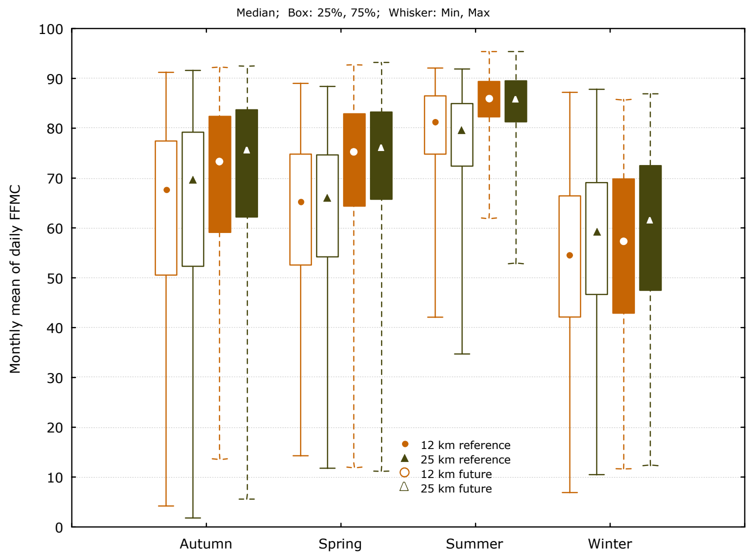



Figure 4.15 - Monthly average of daily FFMC for HIRHAM 12 km simulation (circle point) and HIRHAM 25 km simulation (triangular point) by season, for 1961-1990 scenario (orange boxes) and 2071-2100 scenario (green boxes).

Figure 4.16 presents the FWI projections for future scenario for both analyzed spatial resolutions. The impacts of climate change on DMC, DC, BUI and ISI components of the FWI system are exhibited in Appendix C.

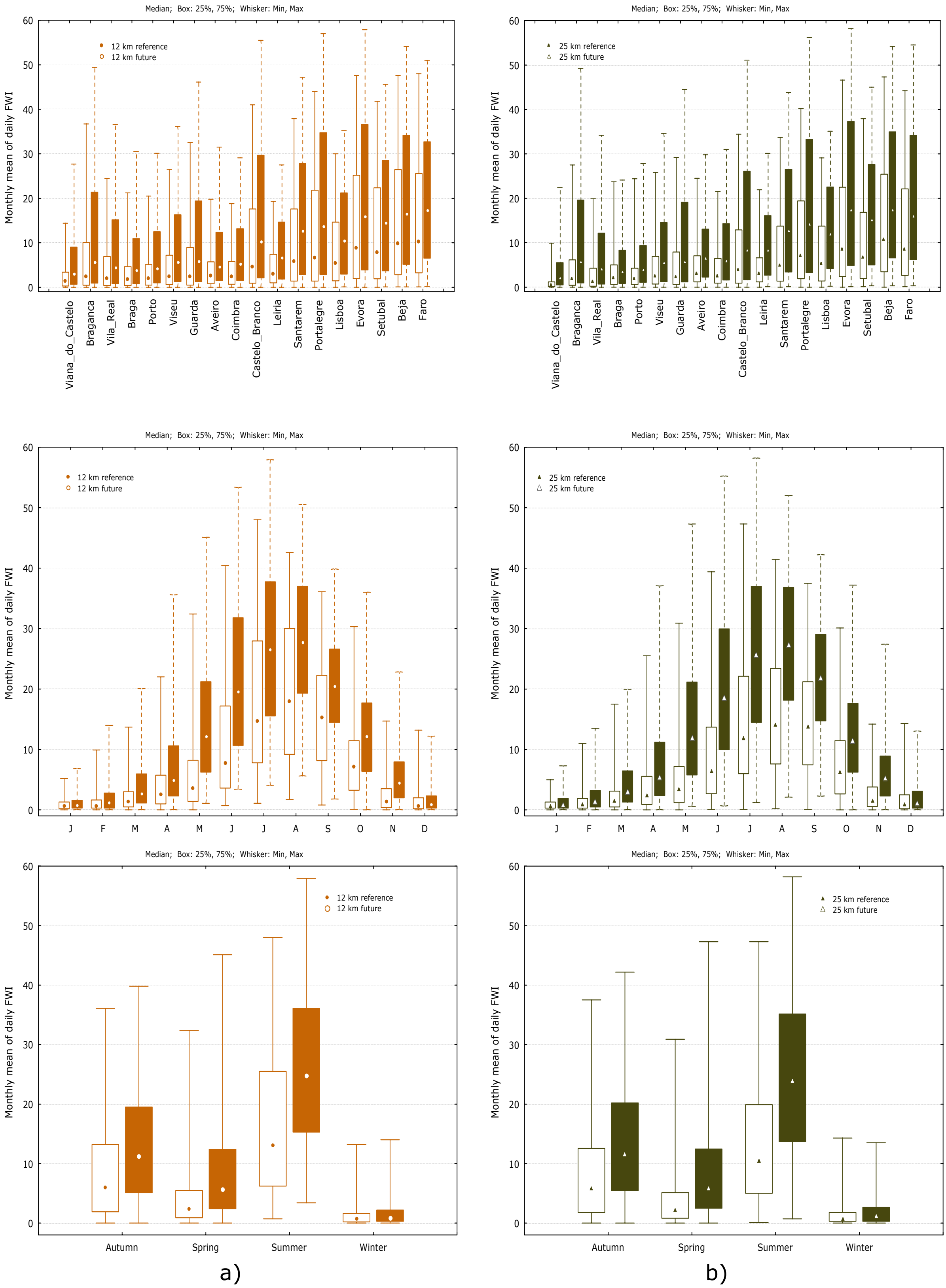



Figure 4.16 - Monthly mean of daily FWI per district, per month and per season, for 2071-2100 scenario (coloured boxes) and 1961-1990 scenario (open boxes) for a) HIRHAM 12 km simulation and b) HIRHAM 25 km resolution.

All the districts present an increase in the FWI index in both simulations. The statistical analysis revealed that there are not significant differences between the FWI projections at 12 km and at 25 km except in summer for some Portuguese districts (Braga, Leiria, Santarém, Lisboa, Évora, Setúbal, Beja, and Faro), where the 25 km simulation shows larger increases.

All seasons experience an increase on the FWI component by the end of XXI in a 2 x $CO_2$ scenario. The month of May registers the highest relative increases. The months of October and November also exhibit considerable increases in the FWI index (Figure 4.16). This could lead to a clear anticipation of the fire season starting and an increase in its length. Marques and Rocha [2003] based on GCM outputs over Portugal have already pointed a possible increase on the fire risk in the beginning of the summer under a 2 x $CO_2$ scenario. There is also a clear FWI increasing trend from north to south, starting in Viana do Castelo district till Faro. The highest values are detected in Évora and Beja, as it is already observed nowadays. Another important feature is the increase on the 25$^{th}$ percentile values. Higher values are observed in future climate for this quantity. This is an important indication on how climate change may impact not only the maximum values but also a positive shift in the minimum ones.

Table 4.3 presents the statistics on the daily FWI values related to the observed large fires by district between 1980 and 2005. The FWI data used is described in §4.2.1 (pp 61). It should be noted that for the full period between 1980 and 2005 there were 2353 large fires registered in the 12 analysed districts. Not all the large fires were considered for the analysis presented in Table 4.3 due to FWI data limitations for the studied period.

The district of Viseu exhibits the highest number of large fires (area burned over 100 ha) for the analysed period (481). The districts of Viseu, Vila Real, Bragança, Castelo Branco, and Coimbra represent 74 % of a total of 2160 large fires considered. Each district is characterized by a different range of FWI values associated to the occurrence of large fire events. The minimum and maximum FWI values range from 0.1 to 21.4 and 32.8 to 81.9, respectively, depending on the district. As already discussed in Chapter 3 the level of risk that each FWI value represents is different among the districts (Table 3.2, pp 42). The impact of climate change on the minimum and maximum FWI values may directly influence the occurrence and extension of large forest fires in Portugal.

Table 4.3 – Daily fire weather index (FWI) for observed large fires (area burned over 100 ha) between 1980 and 2005, by district.

| District | N | FWI minimum | FWI mean | FWI maximum |
|---|---|---|---|---|
| Bragança | 274 | 0.3 | 20.3 | 49.2 |
| Vila Real | 392 | 0.8 | 17.5 | 32.8 |
| Porto | 127 | 2.3 | 14.7 | 42.6 |
| Viseu | 481 | 0.1 | 19.4 | 52.5 |
| Coimbra | 226 | 3.5 | 17.9 | 42.5 |
| Castelo Branco | 236 | 11.1 | 35.2 | 81.9 |
| Portalegre | 52 | 21.4 | 42.2 | 64.8 |
| Santarém | 107 | 9.5 | 25.9 | 42.5 |
| Lisboa | 47 | 13.6 | 33.3 | 62.9 |
| Évora | 36 | 14.0 | 41.7 | 65.7 |
| Beja | 72 | 5.7 | 35.6 | 59.8 |
| Faro | 110 | 0.2 | 28.5 | 79.2 |

As the projections for the 12 km and 25 km resolution are not significantly different for the majority of the Portuguese districts the following analysis is based on the highest resolution simulation outputs. In this sense, Figure 4.17 exhibits the FWI cumulative frequency distribution for each scenario at 12 km resolution by district. To facilitate the discussion the districts are organized by north, centre and south of Portugal.

The obtained cumulative distribution functions clearly show the FWI shift to attain higher values in a future climatic scenario. The districts of the north formed by Viana do Castelo, Bragança, Vila Real, Braga, and Porto show an increase of the maximum FWI range of values from 26-53 to 45-76. The 50$^{th}$ percentile also shows an increase but not so pronounced. The districts in the Centre like Viseu, Guarda, Aveiro, Coimbra, Castelo Branco and Leiria, also present an increase in the FWI maximum values ranging from 39-55 to 55-71 from the reference to the future climatic scenario. The southern districts of Santarém, Portalegre, Lisboa, Évora, Setúbal, Beja and Faro present the highest FWI maximum values in the reference scenario and the same is verified in the future climate. The FWI values between the 25$^{th}$ percentile and the maximum show a clear increase in all southern districts. In this part of the country the FWI ranges from 50-71 and in future climate these values increase to 57-76.

The FWI 90th percentile was selected by the stepwise regression (Chapter 3) as a good predictor for the area burned over Portugal. In this sense, the projected increase on the FWI values may deeply impact the future area burned. This fact may be also related to the increase in the number of large forest fires.

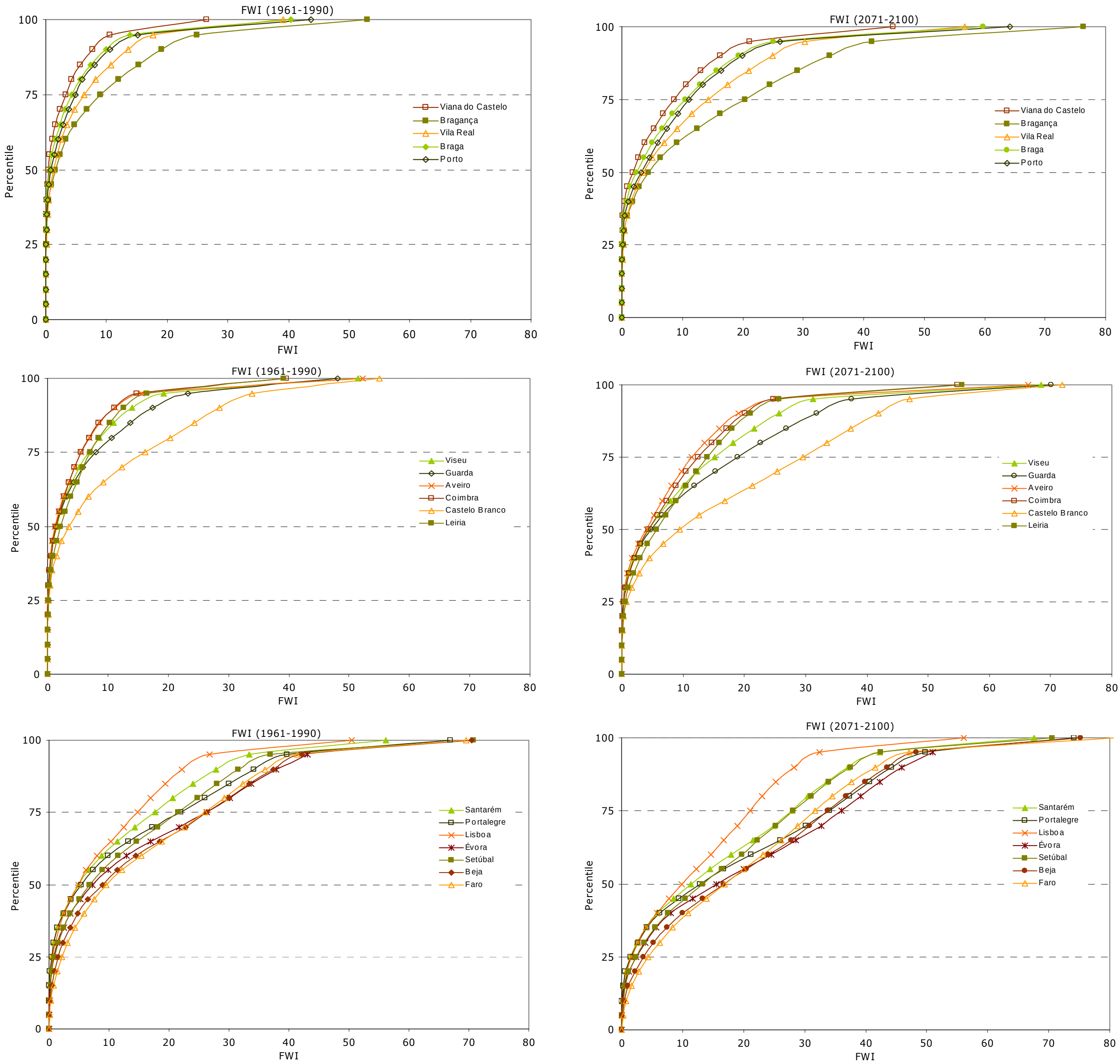



Figure 4.17 - Cumulative frequency distribution of the daily FWI component by district and for each climatic scenario (reference and 2 x $CO_2$) at 12 km resolution. The districts are organized by north, centre and south of Portugal.

The relative frequency analysis for different FWI class of values is another approach to assess the impacts of future climate change on fire weather risk. Based on the 12 km simulation projections, from reference to future climate all Portuguese districts present an increase of the higher FWI class frequency and a reduction of the lowest FWI values (class ranging from 0 to 10) (Appendix C). Depending on the district the first FWI class decreases approximately 10 %. This decrease is accompanied by an increase on the frequency of the subsequent classes in future climate and is different according to the district. The FWI classes between 50-60 and 60-70 do not present any frequency of occurrence in the reference climate. In future these two FWI classes appear in some of the Portuguese districts.

Figure 4.18 presents the differences on the FWI patterns for May, June, July, August, September, and October between future and reference climatic scenarios at 12 km. As previously noted, all the districts across Portugal experience an increase on the FWI component but this is more pronounced in the inner regions. July and August show the highest increases namely in the districts of Bragança, Guarda, and Castelo Branco. These districts form a regional elongated pattern that goes from north to the centre just close to the Spanish border. September and October exhibit a very homogeneous pattern of increase from north to south.

The increase on the fire weather severity values may have a major impact in the area burned and the number of fires in a 2 x $CO_2$ climatic scenario over Portugal.

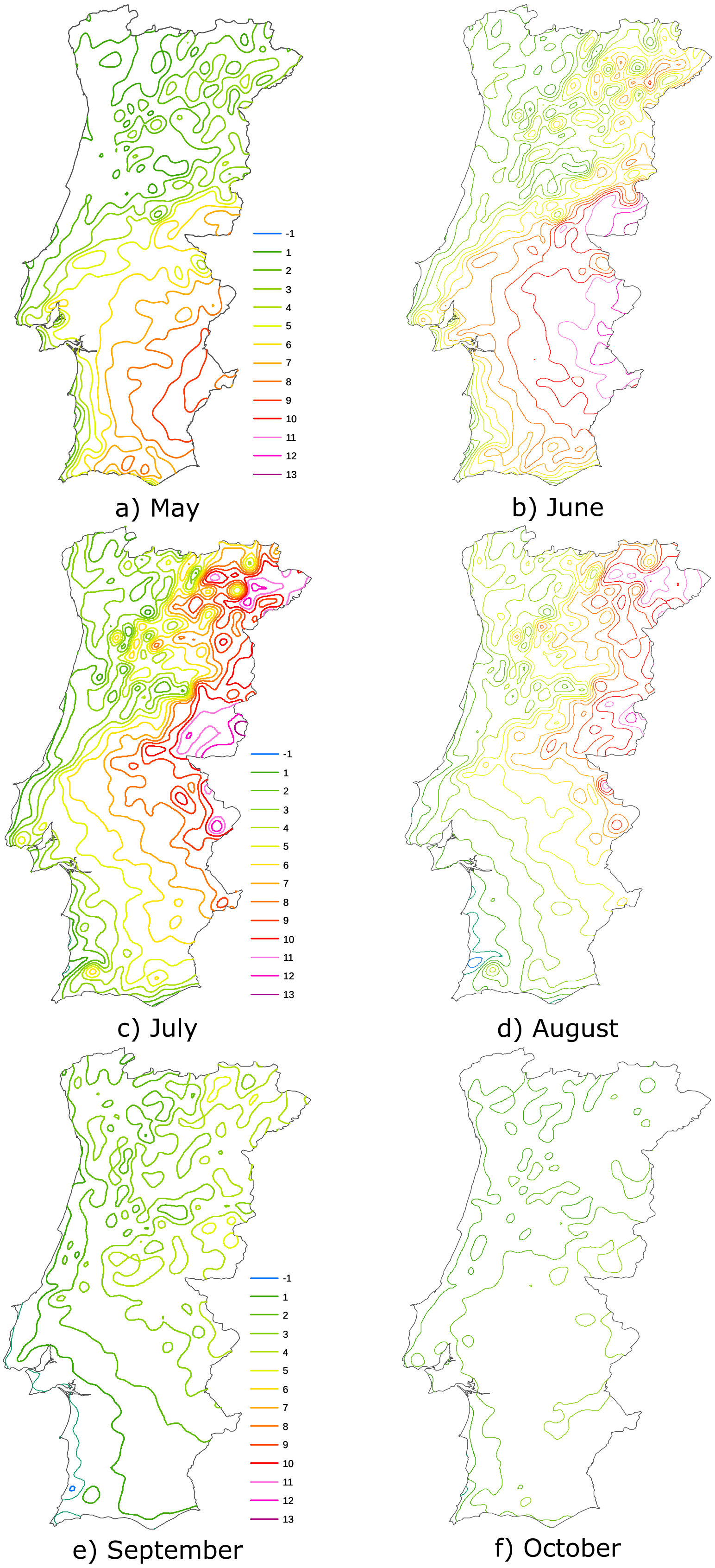



Figure 4.18 - FWI changes between future and reference scenarios, at 12 km resolution, for a) May, b) June, c) July, d) August, e) September, and f) October.

Climate change impact assessment studies constitute an important tool to efficiently and quantitatively discuss the future impacts. Associated to this type of analysis are, as expected, a number of uncertainties and assumptions that bound the obtained results. In this sense, there are some limitations in the present study.

The statistical validation analysis was a complex process and at some extent very exhaustive for an RCM validation procedure. The RCM projections are intended to predict broad weather patterns and trends. They are not intended to match weather patterns on a daily basis but to provide forecasts of monthly and yearly weather, for which daily variability is accounted [Flannigan *et al*., 2002]. The daily evolution of the fire weather variables is fundamental to the establishement of the forest fire severity. The daily precipitation and the dew point temperature data from the RCM were modified in order to have them as close as possible to the observed data recurring to minimal necessary adjustments. Other approaches could have been applied. The first was to superimpose the monthly anomaly data from the RCM outputs onto the observed data. Nevertheless, the availability of observed data is scarce and limited to a reduced number of weather stations and, in addition, this approach would keep constant the future precipitation frequency patterns what could deeply mask the fire weather impact assessment.

Fire weather is only one of the most important factors determining fire risk and fire behaviour; fuels, terrain and suppression are also critical. Prevention strategies and adequate management plans will play a crucial role against the natural conditions, namely meteorology, that in future climate will favour forest fires ignition and propagation. In addition to the natural and structural conditions human influence associated to cultural and social behaviours must also be considered for a better discussion on wildfire activity over Portugal.

## 4.4. Summary and conclusions

The Canadian FWI System that is used operationally by Portuguese authorities during the fire season was selected for the evaluation of the impact of climate change on fire weather risk over Portugal. Daily climatic data were collected from the regional climate model HIRHAM, within the PRUDENCE project at 12 km and 25 km resolution. The FWI components were estimated for both climatic scenarios 1961-1990 (reference) and 2071-2100 following the IPCC SRES A2 scenario (2 x $CO_2$). A statistical analysis was conducted in order to evaluate the performance of the HIRHAM to model the reference climate and also to evaluate the statistical significant differences between reference and future climate.

The reference climate simulation was validated for the 1980-1990 period and for both spatial resolutions. The comparison was performed at 12 meteorological stations that covered the majority of the Portuguese territory. The validation procedure revealed that the HIRHAM presents a slight over-estimation of approximately 2 ºC of the mean temperature mainly in the southern districts of Portugal. In terms of precipitation the 25 km simulation showed a wet bias in the south due mainly to a higher frequency in the small daily rainfall events. A constant correction factor of -1.5 mm day$^{-1}$ was applied between latitudes 37.5N and 39.5N. This correction factor was also applied to the future climate simulation at 25 km resolution. Concerning relative humidity the HIRHAM model presents drier values than the observed at the weather stations. In order to correct the relative humidity field the dew point temperature was evaluated and statistical significant differences were found. The HIRHAM model presents a cold bias in the dew point temperature fields and especially in the south of Portugal and in autumn. A correction factor was applied to the 12 km and to the 25 km simulation based on monthly discretization. The correction factors were applied to the reference and to the future climate simulations for both analysed resolutions. The validation procedure was complex but as fire severity is very dependent on the daily evolution of the fire weather variables this constituted a fundamental step to correctly assess and analyse the impact of future climatic scenario on fire weather risk.

Spring is the season that will suffer the highest increases in terms of fire severity. The FWI index reachs more than 150 % increase in the districts of Guarda and Coimbra. In the south the autumn will be the most impacted season. All the districts will face at least a 100 % increase on the fire weather risk in spring except Lisboa, Setúbal, Beja and Faro. The results point to an anticipation of the fire season starting and an increase in its length. Regarding the spatial distribution, the north and central part of the country exhibit the highest enhancements on fire weather severity during the summer months. Another important feature is the increase in the 25$^{th}$ percentile of the FWI values expected with the future climate. This is an important indication on how climate change may impact not only the maximum values but also a positive shift in the minimum ones.

Class frequency and percentile estimations of the FWI index were evaluated for both climates and for each Portuguese district at 12 km resolution. FWI projections point to an increase of the average and extremes values in all Portuguese districts. The obtained cumulative frequency functions clearly show the fire weather severity shifts to higher values in a future climatic scenario. The districts of the north and centre show the highest increases in the FWI cumulative distribution. As the FWI index is closely related to the fire intensity level the projected impacts may deeply influence the fire suppression strategy and the vegetation dynamics.

As was established in Chapter 3, the area burned and the number of fires in Portugal are strongly linked to the weather and the fire weather risk. So, it is expected that fire activity will increase with a changing climate. In the next chapter the area burned and the forest fire occurrences under a 2 x $CO_2$ climatic scenario will be investigated.

# 5. Climate change impacts on area burned and forest fire occurrences

## 5.1. Introduction

The increase on fire severity can deeply impact the number of fires and the area burned of a region. The way the future climate may interact with the forest fire activity over Portugal constitutes the main objective of this chapter.

The number of studies that have quantified the impacts of climate change on fire activity are very reduced and have only been carried out in specific regions of the globe namely in Canada [Flannigan *et al*., 2005a] and USA [Price and Rind, 1994]. In Europe, this type of assessment has never been conducted.

There are a number of methods available to estimate future area burned. Options include using dynamic vegetation models that include a fire component in the model, landscape fire models where fire ignition and spread is modelled explicitly and using historical relationships between observed area burned and the associated weather and fire weather indexes [Flannigan *et al*., 2005a]. In this work the latter method has been selected because successful relationships have been established between historical area burned and fire occurrences and the weather (§3.3.1, pp 44). These relationships can then be related to future RCM and GCM scenarios to provide estimates of future area burned and number of fires. However, there is the potential problem of extrapolation of relationships beyond the range of observed values. Hence, in a future analysis it is important to use dynamic models of climate and vegetation to estimate future fire activity [Flannigan *et al*., 2005a]. There are other factors such as ignition agents, length of the fire season and fire management that will deeply influence the impact of climate change on fire activity [Flannigan *et al*., 2005b].

In Canada, based on the weather/area burned relationships established by Harrington *et al*. [1983] and Flannigan and Harrington [1988] and on the projections of the Canadian Climate Centre – CCC - model [Flato *et al*., 2000] and the HadCM3 model [Hulme *et al*., 1999], the area burned is projected to increase by 74 % to 118 % in a 3 x $CO_2$ scenario [Flannigan *et al*., 2005a]. The authors stressed that the achieved results suggest a significant increase in area burned in Canada that could have important implications on forests, forestry activities, community protection and carbon budgets. Wotton *et al*. [2003] also predicted that the people-caused ignitions would increase 18 % and 50 % for 2050 and 2100, respectively, for Ontario. In USA, Price and Rind [1994] suggested that the area burned would increase by 78 % for a 2 x $CO_2$ scenario based on a 44 % increase in lighting fire ignitions. Is now under development the projections of future area burned for North America in the scope of air quality impact assessment studies over the US [Hudman *et al*., 2007].

The main objective of this study is to estimate the area burned and the number of fire starts in a 2 x $CO_2$ climatic scenario, over Portugal, based on different spatial resolution climatic scenarios (12 km and 25 km). In order to enhance the spatial differentiation among the different Portuguese regions the analysis was done at the district level.

## 5.2. Data and Methods

To estimate future area burned and number of fires the regional climatic data described and analysed in Chapter 4 were used. Firstly, a summary analysis of the forest fire statistics is presented – *Fire activity trends in Portugal*. The used data and applied methodology is described under – *Fire/weather relationships and applied climatic data*.

### 5.2.1. Fire activity trends in Portugal

In Portugal, the annual average area burned between 2000 and 2005 was 107 % higher than the 1990s which was already 40 % higher than the 1980s annual average (Figure 5.1).

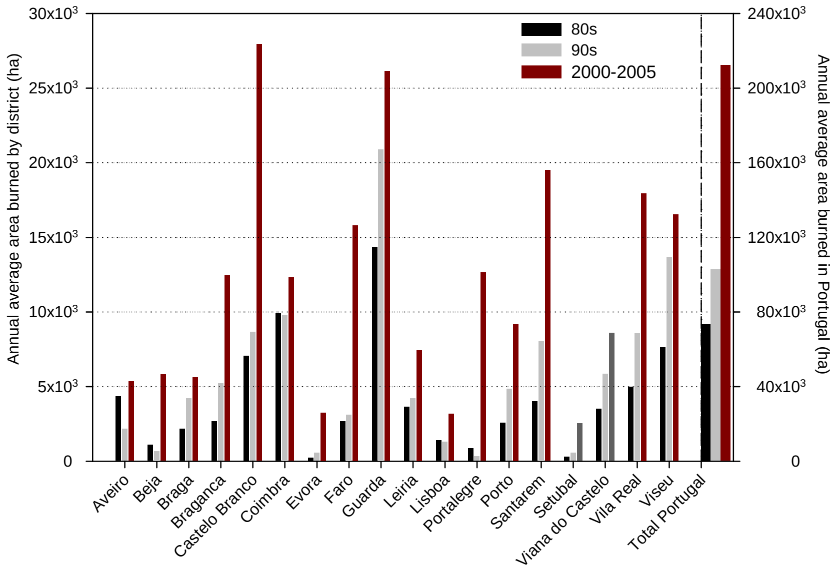



Figure 5.1 - Annual average area burned for the 1980s, 1990s and 2000-2005 period, by Portuguese district and for Portugal. Dashed line separates the districts vertical axis (left side) from the total Portugal vertical axis (right side).

It is clear the increase of the anual area burned in the most recent years mainly because of the devastating 2003 and 2005 fire seasons. Castelo Branco, Setúbal, Portalegre, Évora, Beja, and Faro are the districts that faced the highest increases since the year 2000. The southern districts of Portalegre, Évora, and Beja show the largest increases in the area burned. The referred districts present favourable meteorological conditions to fire ignition and spreading, however the type of forestry of this region had an important role on its prevention. Though, in the last few years an increase of the area burned was observed in these regions and this may be closely connected to an alteration in social behaviour, i.e., there is an increasing brushland expansion in these areas due mainly to land abandonment, and the typical forest species, i.e., Cork oak (*Quercus suber*) and Holm oak (*Quercus rotundifolia*), resistant to fire, have been facing a decline. In addition, climate may also contribute to this trend. In terms of the average annual area burned, Portalegre district increased from 331.3 ha in the 1990s to 12657.8 ha in the period 2000-2005. The most severe forest fire in the last 26 years occurred in Portalegre district in 2003 consuming almost 41,100 ha of forest and brushlands (Figure 5.2).

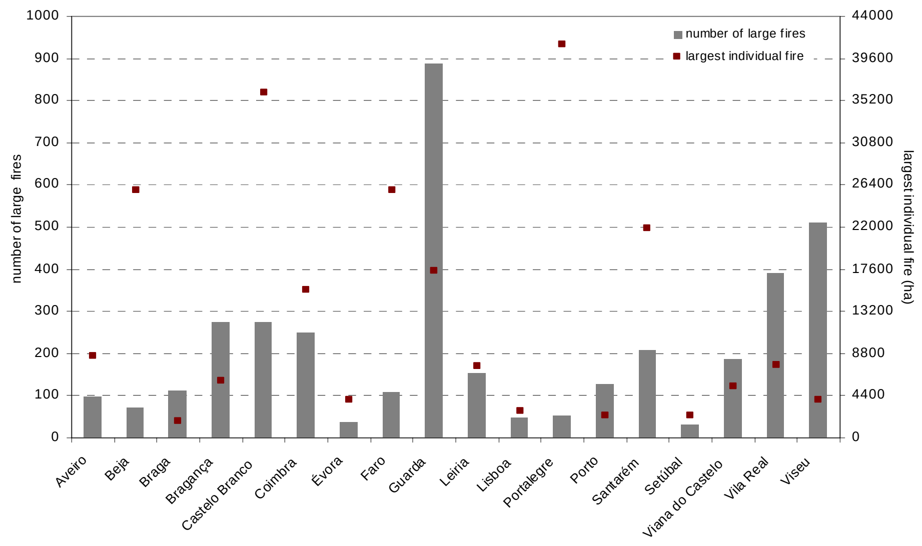



Figure 5.2 - Number of large fires (area burned above 100 ha) and largest individual fire, between 1980 and 2005, by Portuguese district.

According to Figure 5.2, the highest number of large fires (defined by the Portuguese authorities as over 100 ha of area burned) occurs in the Guarda district. The regions that experience the highest number of large fires do not necessarily experience the most severe ones. Viseu district has the second highest number of large fires but the most severe fire did not reach 4400 ha of area burned. It is important to point that the southern districts of Beja, Faro and Portalegre registered the largest individual fires with 25899 ha, 25894 ha and 41079 ha of area burned, respectively (Figure 5.2). The years of 1985, 1995, 1998, 2000, 2003 and 2005 accounted with more than 200 large fires each. Usually the large fires are responsible for the majority of the area burned in Portugal despite its low frequency of occurrence. In 2003 and 2005 large fires accounted for 93.1 % and 85.1 % of total area burned, respectively. These occurrences represented less than 1 % of total number of fires [DGRF, 2006b].

### 5.2.2. Fire weather relationships and applied climatic data

In Chapter 3 statistically significant correlations have been established between the area burned, the number of fires and the weather for 12 Portuguese districts. The obtained statistical models represent an adequate tool to estimate the area burned and the number of fires in Portugal. The climatic data and the fire weather risk projections presented in Chapter 4 were used as input to the developed statistical models. So, the regressions were used to estimate the monthly area burned and the monthly number of fires in the reference and in the future climate.

However, when applying the obtained regression models to the future climatic scenario the estimated values for area burned and the number of fires had no physical meaning. A detailed analysis of the fire weather and the FWI components revealed that these variables show a substantial increase in future climate (§4.3.2, pp 80). This is mainly related to the increase that some of the FWI components namely the BUI and the DC register in future climatic scenario restricting the range of application of the developed regression models. Hence, new regression models were established for the assessment of the impact of future climatic scenario on the area burned and on the number of fires. It is important to stress that the regression models developed in Chapter 3 represent the most adequate tool to evaluate the forest fire activity in Portugal under present climate conditions.

Having in mind that the fire weather is one of the most important factor that control fire activity in Portugal, other variables that also presented high correlations with the area burned and the number of fires were considered in the new regression analysis.

According to Viegas *et al*. [1992] the fine fuels are the most directly involved in the ignition and propagation of forest fires in Portugal. The fine fuel moisture code FFMC is a good indicator of the moisture content of fine fuels and is directly related to the ignition potential. Additionally, the monthly mean of the daily maximum temperature in Portugal is capable to explain alone approximately 71 % and 58 % of the monthly area burned and the monthly number of fires, respectively (Figure 3.6, pp 48). In this sense, the monthly mean of daily maximum temperature (TX) and the monthly mean of the daily mean fine fuel moisture code (FFMC) were the selected variables to forecast future area burned and number of fires in Portugal.

The districts of Portalegre, Évora, and Beja were analyzed as a group because this increases the variance explained in the number of fire occurrences (as previously described in §3.3.2, pp 53). Using SAS software a multiple regression analysis was performed for each district with the natural logarithm of monthly area burned and the natural logarithm of monthly number of fires as the predictand and the monthly mean of daily maximum temperature and the monthly mean of daily FFMC as predictors. The analysis was performed at a 0.05 significance level.

## 5.3. Results and Discussion

In this section the projected area burned and number of fires under a future climatic scenario are presented. Firstly the projected area burned is discussed – *Area burned in* *a future climatic scenario*; secondly the future number of fires are analysed – *Number of fires in a future climatic scenario*.

### 5.3.1. Area burned in a future climatic scenario

Table 5.1 presents the regression models obtained by multiple regression and the explained variance (in %) by TX and FFMC for the natural logarithm of monthly area burned for each district. All obtained regressions are highly significant indicating that the model explains a significant portion of the variation in the data. The variance explained for area burned ranges from 58 % to 71 % depending on the district.

The obtained regression models were used to estimate the area burned for reference and future climate for both HIRHAM regional climate model spatial resolutions.

Table 5.1 - Regression model selected by multiple regression for the natural logarithm of the monthly area burned (TX in degrees Celsius).

| District | Regression model Ln(ab) | Variance explained (%) | N | p |
|---|---|---|---|---|
| Bragança | $-3.245 + 0.289TX + 0.0119FFMC$ | 59 | 300 | <0.0001 |
| Vila Real | $-4.248 + 0.208TX + 0.0593FFMC$ | 61 | 300 | <0.0001 |
| Porto | $-7.961 + 0.389TX + 0.0555FFMC$ | 58 | 300 | <0.0001 |
| Viseu | $-5.281 + 0.246TX + 0.0685FFMC$ | 60 | 138 | <0.0001 |
| Coimbra | $-6.899 + 0.338TX + 0.0408FFMC$ | 64 | 300 | <0.0001 |
| Castelo Branco | $-5.125 + 0.317TX + 0.0237FFMC$ | 71 | 236 | <0.0001 |
| Santarém | $-6.452 + 0.355TX + 0.0140FFMC$ | 67 | 180 | <0.0001 |
| Lisboa | $-6.245 + 0.353TX + 0.0174FFMC$ | 64 | 300 | <0.0001 |
| Portalegre, Évora and Beja | $-4.351 + 0.269TX + 0.0149FFMC$ | 58 | 300 | <0.0001 |
| Faro | $-8.732 + 0.413TX + 0.0257FFMC$ | 63 | 300 | <0.0001 |

Table 5.2 presents the 2 x $CO_2$/1 x $CO_2$ area burned ratio predictions using the HIRHAM 12 km and 25 km simulations.

Table 5.2 - Ratio of 2 x $CO_2$/1 x $CO_2$ area burned, by district, using the HIRHAM model outputs at 12 km and 25 km resolution

| District | area burned ratio | |
|---|---|---|
| | **12 km** | **25 km** |
| Bragança | 7.51 | 7.35 |
| Vila Real | 4.94 | 5.27 |
| Porto | 6.97 | 7.14 |
| Viseu | 6.40 | 5.74 |
| Coimbra | 6.25 | 6.53 |
| Castelo Branco | 6.69 | 7.09 |
| Santarém | 5.11 | 5.81 |
| Lisboa | 3.71 | 3.04 |
| Portalegre, Évora and Beja | 3.88 | 4.19 |
| Faro | 4.10 | 5.08 |
| All districts | 5.56 | 5.72 |

The 25 km simulation presents higher 2 x $CO_2$/1 x $CO_2$ area burned ratios than the 12 km HIRHAM simulation for the majority of the analyzed districts. For all analyzed districts the HIRHAM 12 km simulation suggested an average ratio of 5.56 whereas the 25 km simulation has a ratio of 5.72. This is mainly related to the slightly higher increase of the FFMC index in the 25 km simulation.

The Wilcoxon score test was applied in order to evaluate the statistical significance between the area burned ratios obtained for both analyzed spatial resolutions. At a 0.05 significance level there is no statistical significant difference between both datasets. Table 5.3 presents the observed annual area burned for the 1980-1990 period along with the predicted area burned for each district and all analyzed districts for the 2 x $CO_2$ scenario. The 1980-1990 period was used for the reference climate validation (§4.3.1, pp 68) and is also considered in the area burned analysis. The area burned projections were based on the average ratios obtained from both simulations (from Table 5.2) because no statistical significant difference was detected between HIRHAM 2 x $CO_2$/1 x $CO_2$ ratios at 12 km and 25 km. In order to forecast future annual area burned the obtained average 2 x $CO_2$/1 x $CO_2$ ratios by district were multiplied by the average annual area burned observed between 1980 and 1990.

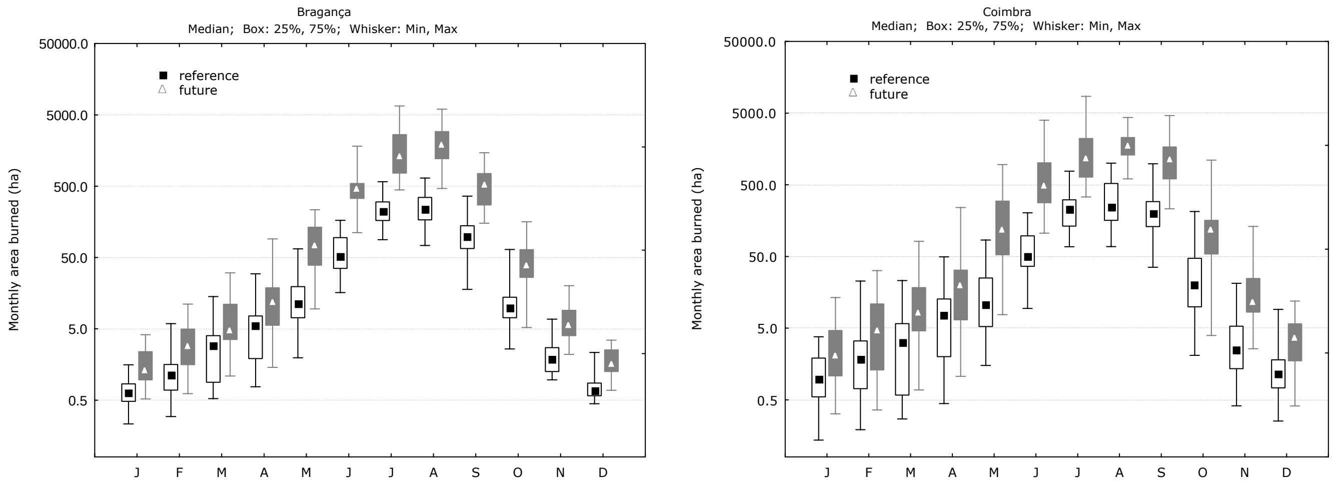
Table 5.3 - Annual area burned (ha) by district, observed in 1980-1990 period and predicted for the 2 x $CO_2$ climate, considering the average 2 x $CO_2$/1 x $CO_2$ ratio between HIRHAM 12 km and HIRHAM 25 km simulations. Percent of total annual area burned by district for observed and 2 x $CO_2$ scenario and percent of increase in area burned in future scenario.

| **District** | **Observed annual area burned in 1980-1990** | | **2 x $CO_2$ area burned** | | **(2 x $CO_2$ – obs) / obs** |
|---|---|---|---|---|---|
| | **(ha)** | **(%)** | **(ha)** | **(%)** | **(%)** |
| Bragança | 2804.5 | 5.3 | 20837.4 | 6.8 | 643 |
| Vila Real | 5717.1 | 10.8 | 29185.8 | 9.5 | 411 |
| Porto | 2970.5 | 5.6 | 20956.9 | 6.8 | 606 |
| Viseu | 9064.7 | 17.1 | 55022.7 | 18.0 | 507 |
| Coimbra | 11089.4 | 20.9 | 70861.3 | 23.2 | 539 |
| Castelo Branco | 6897.5 | 13.0 | 47523.8 | 15.5 | 589 |
| Santarém | 4160.6 | 7.9 | 22716.9 | 7.4 | 446 |
| Lisboa | 5717.1 | 10.8 | 19295.2 | 6.3 | 238 |
| Portalegre, Évora and Beja | 2017.6 | 3.8 | 8141.0 | 2.7 | 304 |
| Faro | 2500.9 | 4.7 | 11479.2 | 3.8 | 359 |
| All districts | 52939.9 | 100.0 | 306020.1 | 100.0 | 478 |

The projections for the 2 x $CO_2$ scenario point to a substantial enhancement of the area burned in the analyzed districts. Table 5.3 presents a strong increase of area burned particularly in Bragança and Porto districts showing increases of 643 % and 606 %, respectively. Almost all districts exhibit enhancements in the area burned above 250 %. In the 1980s, Coimbra district already presented the highest percentage of contribution (20.9 %) to the overall area burned in the 12 analysed districts. In a 2 x $CO_2$ scenario Coimbra also presents the highest contribution to the total area burned and, in addition, this contribution also increases (23.2 %). Almost all districts face an increase in the area burned percentage contributions to the total area burned except the districts of Lisboa, Santarém, and Faro and the southern region formed by Portalegre, Évora, and Beja. Vila Real district also shows a decrease in its contribution percentage. The results seem to point to a north/south dichotomy with higher increases in the north and central part and less in the south. This pattern was already detected in the fire weather severity projections.

From 2000 to 2003, some districts in Portugal already experienced considerable enhancements in the area burned. In 2003 the districts of Lisboa, Beja, Portalegre, and Santarém faced area burned increases, relatively to the 2000-2002 annual average, of 373 %, 1197 %, 4812 % and 1164 %, respectively. The 2003 fire season was characterized by extreme fire weather conditions [Viegas *et al*., 2006; Trigo *et al*., 2006], which associated with physical and structural conditions led to a disastrous fire season in Portugal.

The monthly distribution of the area burned for reference and future climate is presented in Figure 5.3 for Bragança and Coimbra districts. The remaining districts are presented in Appendix D. As can be seen these districts present a clear increase of the area burned during the summer months of June, July, August, and September. In addition, it is possible to detect the raise of the area burned at the beginning of the fire season in April and by the end of the summer in October. The increase that can be identified early in the year and in the beginning of the autumn may reflect what can be denominated as the anticipation of the fire season and its temporal extension. As detected in the reference climate, July and August exhibit the highest mean area burned values under future climatic scenario.




a) b)

Figure 5.3 – Monthly area burned (ha) distribution for reference and future climate for a) Bragança and b) Coimbra districts.

Table 5.4 presents the percentage of annual area burned in terms of forested land (forestry and shrubland) assuming that the actual forested area would be kept constant in future.

Table 5.4 - Percentage of annual area burned in terms of forested land (ha) between 1980 and 1990 and for the future scenario.

| **District** | **Forested area (ha)** | **Percentage of forested area burned (%)** | |
|---|---|---|---|
| | | **1980-1990** | **2 x $CO_2$ scenario** |
| Bragança | 374898 | 0.7 | 5.6 |
| Vila Real | 271257 | 2.1 | 10.8 |
| Porto | 121909 | 2.4 | 17.2 |
| Viseu | 327455 | 2.8 | 16.8 |
| Coimbra | 279824 | 4.0 | 25.3 |
| Castelo Branco | 474940 | 1.5 | 10.0 |
| Santarém | 424769 | 1.0 | 5.3 |
| Lisboa | 93232 | 6.1 | 20.7 |
| Portalegre, Évora and Beja | 1404895 | 0.1 | 0.6 |
| Faro | 288730 | 0.9 | 4.0 |

For the period between 1980 and 1990 the annual area burned in terms of the district forested area is highest in Lisboa (6.1 %) followed by Coimbra (4 %). By the end of the XXI century this percentage increases in all analysed districts and reaches its maximum in Coimbra with 25.3 % of the forested land being destroyed by the fire.

### 5.3.2. Number of fires in a future climatic scenario

Table 5.5 presents the statistical models obtained by multiple regression and the variance explained by TX and FFMC for the natural logarithm of the monthly number of fires. According to Table 5.5, the variance explained by TX and FFMC ranges from 46 % in Portalegre, Évora, and Beja region to 69 % in Santarém. All districts present high statistical significant regression models for the natural logarithm of the monthly number of fires.

Table 5.5 - Regression model selected by multiple regression for natural logarithm of monthly number of fires (nf) (TX in degrees Celsius).

| District | Regression model Ln(nf) | Variance explained (%) | N | p |
|---|---|---|---|---|
| Bragança | $-1.696 + 0.194TX + 0.00331FFMC$ | 51 | 300 | <0.0001 |
| Vila Real | $-2.735 + 0.157TX + 0.0399FFMC$ | 54 | 300 | <0.0001 |
| Porto | $-6.843 + 0.348TX + 0.0542FFMC$ | 49 | 300 | <0.0001 |
| Viseu | $-2.220 + 0.137TX + 0.0505FFMC$ | 51 | 138 | <0.0001 |
| Coimbra | $-4.548 + 0.196TX + 0.0452FFMC$ | 63 | 300 | <0.0001 |
| Castelo Branco | $-3.023 + 0.179TX + 0.0258FFMC$ | 66 | 236 | <0.0001 |
| Santarém | $-3.736 + 0.216TX + 0.00740FFMC$ | 69 | 180 | <0.0001 |
| Lisboa | $-4.287 + 0.296TX + 0.00895FFMC$ | 47 | 300 | <0.0001 |
| Portalegre, Évora and Beja | $-2.393 + 0.137TX + 0.0180FFMC$ | 46 | 300 | <0.0001 |
| Faro | $-4.737 + 0.232TX + 0.0199FFMC$ | 53 | 300 | <0.0001 |

The obtained regression models were used to estimate the number of fires for reference and future climate for both HIRHAM regional climate model spatial resolutions. Concerning the number of fires both simulations present almost the same ratio of increase (Table 5.6). In average, for all analyzed districts the number of fires starts had a ratio of 3.17 for the 12 km simulation and 3.18 for the 25 km simulation. The number of fires projections were based on the average ratios obtained from both simulations (from Table 5.6) because no statistical significant difference was detected between HIRHAM 2 x $CO_2$/1 x $CO_2$ ratios at 12 km and 25 km.

Table 5.6 - Ratio of 2 x $CO_2$/1 x $CO_2$ number of fires, by district, using the HIRHAM model outputs at 12 km and 25 km resolution

| District | Number of fires ratio | |
|---|---|---|
| | 12 km | 25 km |
| Bragança | 3.44 | 3.37 |
| Vila Real | 3.18 | 3.33 |
| Porto | 5.79 | 5.86 |
| Viseu | 3.00 | 2.78 |
| Coimbra | 3.24 | 3.29 |
| Castelo Branco | 3.04 | 3.14 |
| Santarém | 2.66 | 2.87 |
| Lisboa | 2.98 | 2.50 |
| Portalegre, Évora and Beja | 2.06 | 2.15 |
| Faro | 2.26 | 2.55 |
| All districts | 3.17 | 3.18 |

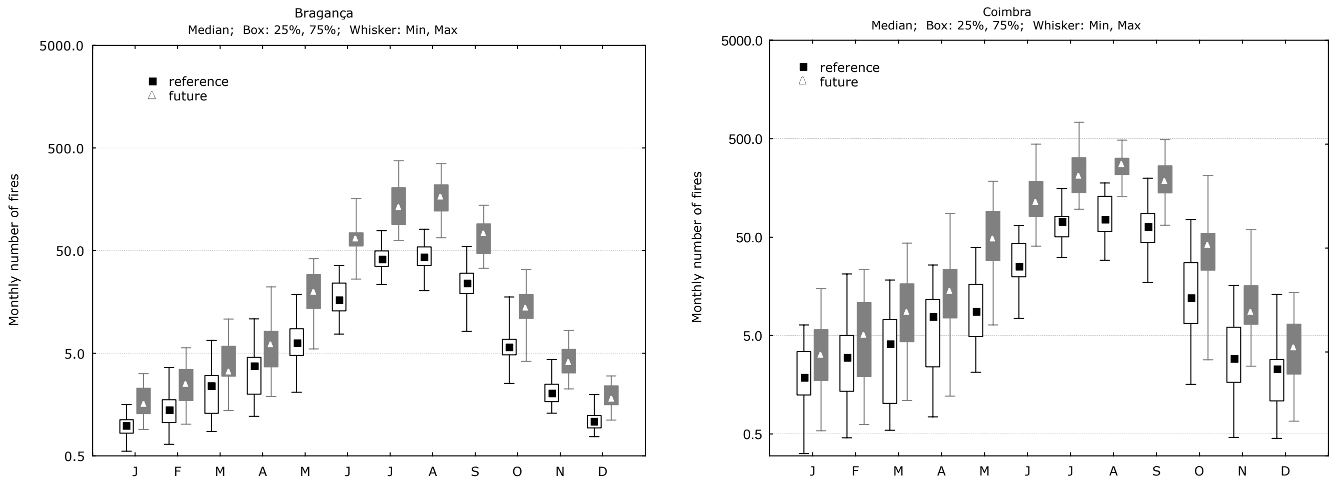
Table 5.7 presents the observed annual number of fires for the 1980-1990 period along with the predicted number of fires for each district and all analyzed districts for the 2 x $CO_2$ scenario.

Table 5.7 - Annual number of fires by district, observed in 1980-1990 period and predicted for the 2 x $CO_2$ climate, considering the average 2 x $CO_2$/1 x $CO_2$ ratio between HIRHAM 12 km and HIRHAM 25 km simulations. Percent of annual number of fires by district for observed and 2 x $CO_2$ scenario and percent of increase in number of fires in future scenario.

| District | Observed annual number of fires in 1980-1990 | (%) | 2 x $CO_2$ number of fires | (%) | (2 x $CO_2$ – obs) / obs (%) |
|---|---|---|---|---|---|
| Bragança | 154 | 3.2 | 524 | 2.9 | 241 |
| Vila Real | 455 | 9.6 | 1481 | 8.2 | 226 |
| Porto | 1334 | 28.1 | 7771 | 43.2 | 483 |
| Viseu | 951 | 20.0 | 2748 | 15.3 | 189 |
| Coimbra | 626 | 13.2 | 2044 | 11.4 | 227 |
| Castelo Branco | 483 | 10.2 | 1492 | 8.3 | 209 |
| Santarém | 205 | 4.3 | 567 | 3.1 | 177 |
| Lisboa | 307 | 6.5 | 841 | 4.7 | 174 |
| Portalegre, Évora and Beja | 131 | 2.8 | 276 | 1.5 | 111 |
| Faro | 108 | 2.3 | 260 | 1.4 | 140 |
| All districts | 4754 | 100.0 | 18004 | 100.0 | 279 |

According to Table 5.7, in a 2 x $CO_2$ scenario all districts show an increase in the number of fire starts. Porto district accounts with the highest contribution (43.2 %) to the total number of fires, as was already detected in the observed data (28.1 %). All districts register a decrease in its contribution to the total number of forest fires but Porto exhibits a 15 % increase. Within each district the percentages of increase in the number of fires are above 150 % except the southern region of Portalegre, Évora and Beja and Faro. The maximum is exhibited in Porto district with an increase of 483 %.

The monthly distribution of the number of fires for both climatic scenarios is presented in Figure 5.4 for Bragança and Coimbra districts. The remaining districts are presented in Appendix D. As already identified in the area burned analysis the months of June, July, August, and September present the highest increases in the monthly number of fires due to climate change. It is interesting to see that the months of March and November register a clear increase on the number of forest fires in almost all districts. This represents an important outcome due mainly to the fire management repercussions that an anticipation of the fire season may lead to. These projections clearly put in evidence the most demanding efforts of the fire agencies in order to face this new reality derived from climate change.




a) b)

Figure 5.4 – Monthly number of fires distribution for reference and future climate for a) Bragança and b) Coimbra districts.

From Table 5.3 and Table 5.7 it is possible to verify that each district shows higher percentages of increase in the area burned values than in the number of fires in a future 2 x $CO_2$ scenario. Lisboa is the only district presenting similar percentages of enhancement in the number of fires and in the area burned. The average of increase concerning all districts is also higher for the area burned (478 %) than the number of fires (279 %). Additionally, each district presents its own pattern of raise. These results suggest a significant increase in area burned and in the number of fires in Portugal with potential important environmental, social and economic impacts.

From the foreseen area burned and number of fires it is possible to estimate the average increase of the area burned by fire in future climate. In average between 1980 and 1990 each fire consumed 11.1 ha of forest and shrubs. In a future climate the area burned by fire will be 17 ha. The increase of almost 6 ha of area burned per fire may represent a dramatic demand for the ecosystems and for the fire fighting resources.

In this study not all districts were analyzed but the fire weather projections for a 2 x $CO_2$ scenario (§4.3.2, pp 80) point to an aggravation of these conditions in all Portuguese districts. The projected values for area burned and number of fires obtained in this study are much higher than the projections for Canada. In Canada, based on GCM outputs, it was projected that by the end of XXI century area burned could increase from 74 % to 118 % in a 3 x $CO_2$ scenario [Flannigan *et al*., 2005a]. Canada and Portugal have completely different climatology and fire statistics mainly related to different factors like fuel type, lighting conditions, forest management and suppression activities. In addition the climate change projections are stronger over southern Europe, namely Portugal, than in Canada [IPCC, 2007].

This study also revealed that the best historical relationships established between the area burned and the number of fires and the weather and the FWI components for current climatic conditions (Chapter 3) had to be re-evaluated in order to be applied under future climatic scenarios. The best tool to currently diagnose the forest fire activity in Portugal could not be applied based on the same assumptions in a 2 x $CO_2$ scenario. This may constitute an important outcome regarding the limitations of today's developed statistical analysis and its application under future climatic scenarios.

Some limitations can be pointed out. Besides the climate change projections uncertainties, the land use patterns and main fuel characteristics were considered constant from reference to future scenario. Changes in fuel load were also not considered and thus not allowing for the carbon dioxide fertilization on vegetation. Human behaviour and land-use changes in future climate were not considered in the fire ignitions (natural and anthropogenic) projection. The projected numbers of area burned and number of fires should take into account all these aspects.

## 5.4. Summary and conclusions

This work investigated the area burned and the number of fires over Portugal in a 2 x $CO_2$ scenario for two different spatial resolutions (12 km and 25 km) climatic scenarios. In order to project future area burned and number of fires, the already established relationships between the weather and the FWI System components and the area burned and fire occurrences between 1980 and 2004 had to be re-evaluated. The monthly mean of daily maximum temperature (TX) and the monthly mean of the fine fuel moisture code (FFMC) explained 58 % to 71 % of the variance in the monthly area burned and 46 % to 69 % of the monthly number of fires depending on the district. This study revealed that there are no statistical significant differences between the 12 km and the 25 km 2 x $CO_2$/1 x $CO_2$ ratios for area burned and number of fires. The results point to a substantial increase on the area burned and on the number of fire starts ranging from 238 % to 643 % and 111 % to 483 %, respectively, depending on the district.

The monthly distribution of the area burned and number of fires indicates that an earlier fire season starting may be expected under future climatic scenario. Some districts present increases on the monthly area burned in April. On the other hand, the increases on the monthly number of fires may be detected as early as February in some Portuguese districts like Viseu and Coimbra. These findings point to important modifications on the fire activity annual cycle over Portugal. In addition the average area burned by fire is projected to increase almost 6 ha.

The environmental, social and economic costs of the projected increases in area burned and number of fires in Portugal can dramatically impact the organizational structures that deal with this problematic and the society in general. The impact of forest fire emissions to the atmosphere is also affected by the projected increases in area burned. Nowadays, the air quality forecasting system implemented in Portugal has been registered operational difficulties during the summer season due to the lack of forest fires emissions in the modelling system [Monteiro *et al*., 2005a]. Furthermore, the increase of the number of forest fires in the wildland-urban interface is conducting to a higher number of registered air pollution episodes in the air quality networks [Miranda *et al*., 2005d]. The potential impacts in the air quality management policies and international commitments already signed by Portugal, like the Kyoto Portugal, may have to be re-evaluated in order to include these new findings.

In the next chapter the impact of climate change and future area burned on forest fire emissions and consequently on regional air quality will be assessed and discussed.

# 6. Forest fire impacts on air quality in a future climatic scenario

## 6.1. Introduction

Anthropogenic and biogenic emissions are responsible for photo-oxidants, particulate matter and acidifying gases concentration's increases, which may influence climate at regional scale, and vice-versa. The regional distribution of the air pollutants concentrations is very important since it affects human health, vegetation and animals. Anthropogenic emissions are leading climate change; on the other hand climate change is impacting the pollutants concentrations and its distribution in the atmosphere. This feedback mechanism forms a non-linear loop of relationships between emissions and chemical and physical processes in the atmosphere.

Among these atmospheric chemical species, $O_3$ is of primary concern due to its tropospheric oxidant power and to its greenhouse effect [Gauss *et al*., 2006]. As a result of the increase of ozone precursor's emissions, namely nitrogen oxides, tropospheric ozone concentrations doubled since the end of the XIX century [Brasseur *et al*., 2003]. Ozone is an extremely reactive chemical that has been shown to reduce visibility and have harmful effects on human health, crops production and natural areas [Keyes *et al*., 2001].

Particulate matter is an air pollutant consisting of particles that can be solid, liquid or both, and represent a complex mixture of organic and inorganic substances. These particles vary in size, composition and origin. The coarse fraction is called $PM_{10}$ (particles with an aerodynamic equivalent diameter smaller than 10 µm) and the smaller or fine particles are called $PM_{2.5}$ (with an aerodynamic equivalent diameter smaller than 2.5 µm). The size of the particles also determines the time they spend in the atmosphere. While sedimentation and precipitation removes $PM_{10}$ from the atmosphere within few hours of emission, $PM_{2.5}$ may remain there for days or even a few weeks. Consequently, these particles can be transported over long distances.

High levels of PM are associated with adverse health effects, ecosystem damage, and degraded visibility [Goswami *et al*., 2002; Andersen *et al*., 2004]. According to the most recent report on PM transboundary pollution in Europe [EMEP, 2007], 50 % of the sites reported higher annual mean concentrations of $PM_{10}$ in 2005 compared to 2004, and for the majority of these sites the increase was above 10 %. The higher $PM_{10}$ and $PM_{2.5}$ levels can only partly be explained by emission increases in a few countries, while the largest increase is due to meteorological conditions, i.e. by suppression of pollutants dispersion in the stable atmosphere over northern parts of Russia and by smaller wet deposition due to less precipitation over most of Europe in 2005 compared to 2004 [EMEP, 2007].

Particulate matter may also play an important role in climate change. Some types of PM may heat the atmosphere, while other particles may have a cooling effect [IPCC, 2007]. Climatologists work to try to better understand the sum of the effects of the varying types of PM on global climate change. PM containing black carbon (often referred to as "soot") is due to incomplete combustion of fossil fuels or biomass. According to the IPCC [2007] black carbon absorbs solar radiation very effectively, and may contribute to climate change. On the other hand, some of the particulates, such as those containing sulfate, scatter sunlight back to space, thus cooling the atmosphere. Regardless of their impact on the climate, particulates are still harmful to human health.

The impact of climate change on air quality, namely on $O_3$ and $PM_{10}$ levels, is one of the main threats to the sustainable development particularly in what concerns human health and environmental resources. The majority of the work on climate/chemistry interactions has been done at global scale namely through the application of Chemistry Transport Models (CTMs) and Climate Chemistry Models (CCMs). Few studies have been done at the regional scale.

Hogrefe *et al*. [2004] present the results for the Eastern United States through downscalling from global to regional scale. The authors analyzed the impacts of regional climate change on air quality and concluded that the simulation for five summers in the 2020s, 2050s and 2080s indicates that summertime average daily maximum 8-hour ozone concentrations increases by 2.7, 4.2 and 5.0 ppb, respectively. In Europe, Zlatev [2002] and Langner *et al*. [2005] present the first studies at regional scale. These studies considered only the impacts of a changing climate on air quality, keeping constant the emissions rate. Both studies point to an increase on photochemical production in future climatic scenarios. In Portugal, this topic was addressed through the application of a cascade of models from global to regional scale to episodic situations [Borrego *et al*., 2000; Carvalho, 2006]. The results point to an increase of the number of days that are favourable to photochemical production in a future scenario and an increase in ozone average concentrations and its variability. Hauglustaine *et al*. [2005] suggest that $O_3$ could increase during the 21$^{st}$ century as a direct consequence of enhanced anthropogenic emissions of $O_3$ precursors like $NO_x$, carbon monoxide (CO) and volatile organic compounds (VOCs). An evaluation of the high-emissions IPCC SRES A2 emissions scenario showed global mean surface $O_3$ increases of about 5 ppb by 2030 and 20 ppb by 2100 [Prather *et al*., 2003]. Based on the ensemble mean of 26 global atmospheric chemistry-transport models, Dentener *et al*. [2006] predicted that by 2030, global surface ozone may increase globally by 4.3±2.2 ppb for the IPCC SRES A2 scenario. The same study points out that the more polluting SRES A2 scenario would compromise the attainment of any existing air quality standard in most industrialized parts of the world by 2030. Under the SRES A2 scenario, Szopa *et al*. [2006] estimated that by 2030, the $O_3$ levels in July may increase up to 5 ppb over Europe.

In a changing climatic scenario forest fire activity is predicted to increase in the Iberian Peninsula and hence higher emissions of pollutants to the atmosphere would be expected.

Smoke is considered as one of the several disturbing effects of forest fires. Its impacts on air quality and human health can be considerable because large amounts of pollutants are emitted into the atmosphere. Smoke from forest fires include $CO_2$, CO, $CH_4$, $NO_x$, ammonia ($NH_3$), PM, non-methane volatile organic compounds (NMVOCs), sulphur dioxide ($SO_2$) and other chemical species [Crutzen and Andreae, 1990; Miranda *et al*., 2005a]. The effects of these emissions are felt at different levels: from the contribution to the greenhouse effect to the occurrence of local atmospheric pollution episodes [Miranda *et al*., 1994; Borrego *et al*., 1999; Simmonds *et al*., 2005]. Air pollution episodes related to forest fire activity have been investigated by several studies in Europe [Miranda, 1998; Miranda, 2004; Hodzic *et al*., 2007]. In a changing climatic scenario forest fires may become an even larger source of air pollutants to the atmosphere [Amiro *et al*., 2001a].

To study climate change impacts on forest fire activity and consequently on air quality, namely on $O_3$ and PM concentrations, it is very important to have climatic scenarios with high temporal and spatial resolution, due mainly to the significance that meteorological variables have on ozone chemical mechanism and on PM dispersion and removal from the atmosphere, but also due to the regional patterns of ozone precursors emissions. In addition, the regional distribution of the air pollutants concentrations is very important since it affects human health, vegetation and animals. In this scope, and in what concerns impact assessment studies, the downscalling of large-scale climatic patterns to the regional scale is essential [Mearns *et al*., 2003]. In this study a limited area of the globe is represented at a very high resolution with a mesoscale model.

The interaction between climate change, forest fires, area burned, air pollutant emissions and the associated impacts on air quality is still poorly understood. In this sense, this study intends to evaluate the effect of a changing climate and future forest fire emissions on the air quality over Portugal. The MM5/CHIMERE [Schmidt *et al*., 2001; Grell *et al*., 1994] air quality modelling system has been applied to assess these relationships.

## 6.2. Data and Methods

Firstly, a brief analysis of the pollutants concentrations in the atmosphere is presented – *Monitored air quality data*. The selected air quality numerical system and the simulation conditions are then described – *Air quality modelling*.

### 6.2.1. Monitored air quality data

In this section the air quality data monitored between 1995 and 2005 is presented. It should be noted that before 1995 the air quality data availability is scarce and confined to the coastal regions of Porto and Lisbon. Additionally, the methodology applied to investigate the relationship between the forest fire activity and the air polluttants concentrations in the atmosphere is described.

The nitrogen dioxide ($NO_2$) and the $PM_{10}$ levels in the atmosphere were the selected pollutants to assess the influence of forest fire activity on air quality. These pollutants are directly emitted by the forest fires and thus may be better related to potential impacts on air quality.

$NO_2$ and $PM_{10}$ concentration values were monitored at the air quality network between 1995 and 2005, and the area burned and the number of fires by district were gathered for the same period. This analysis was focused in three different periods: annual, June to September (JJAS) and August. The daily area burned and the number of fires were correlated with the daily average $PM_{10}$ concentrations and the daily maximum $NO_2$ values, registered at each air quality station, by district. Air quality data were available at twelve districts in Portugal. For each district several air quality stations were considered. Figure 6.1 presents the air quality stations used in the analysis. Only the background stations were considered.

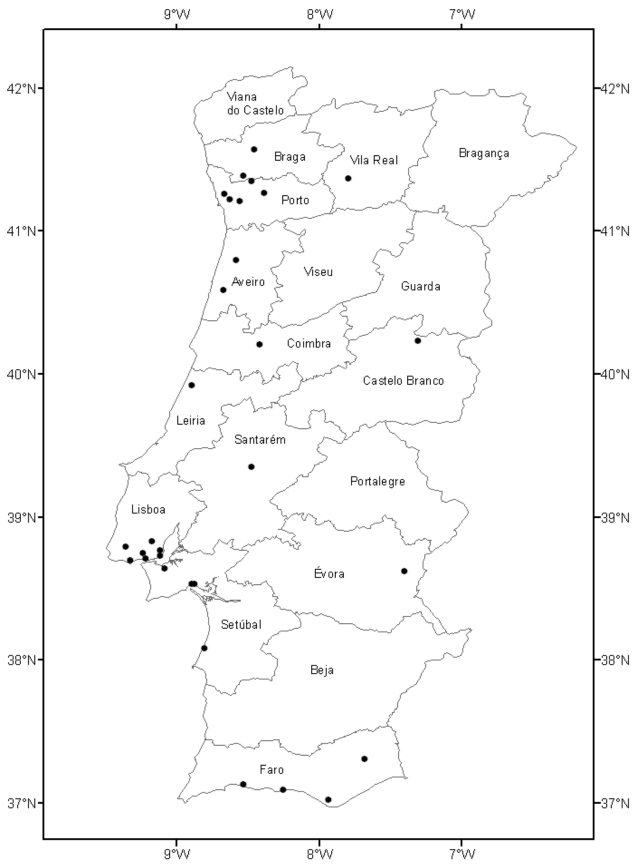
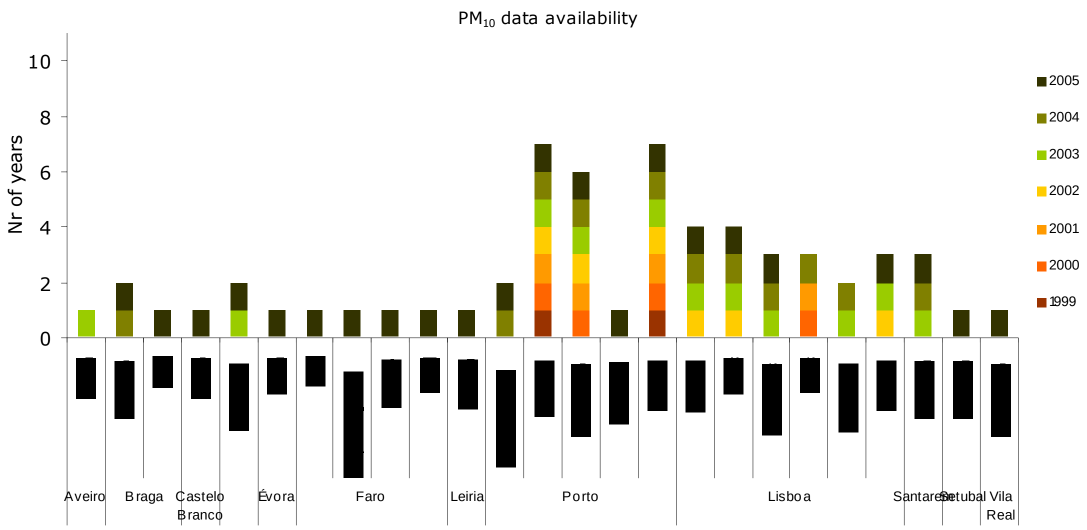
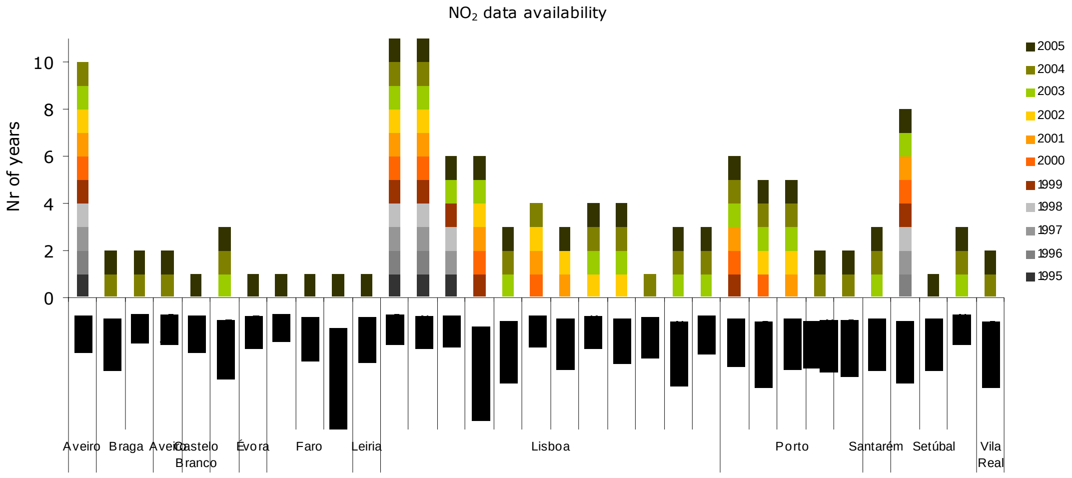



Figure 6.1 - Air quality stations location (dot points) and Portuguese districts identification.

Figure 6.2 presents the $NO_2$ and $PM_{10}$ data availability between 1995 and 2005 by station. As can be noted and considering the minimum monitoring acquisition efficiency of 90 % for $PM_{10}$ and 75 % for $NO_2$ [EC, 2002], the data availability is quite different among all analysed background stations. Some stations namely in Faro district only have one year of data.




a)




b)

Figure 6.2 - Data availability for a) $PM_{10}$ and b) $NO_2$ between 1995 and 2005 by station.

Concerning $PM_{10}$, during this period the maximum value of daily mean $PM_{10}$ concentrations was attained at Leiria district (Ervedeira station), 360 µg $m^{-3}$ and the 75th percentile was always below 50 µg $m^{-3}$, except in Aveiro district (not shown). The $NO_2$ values registered the highest maximum concentrations in the urban districts of Lisboa, Aveiro, Setúbal, and Porto. This reflects the influence of traffic emissions on the measured values at the air quality stations. It is important to stress that some of the stations used in the analysis reflect an urban background atmosphere. Concerning the monthly distribution, the median of the $NO_2$ maximum concentrations exhibits a slight decrease during the months of May, June, July, and August. This fact may be closely related to the increase of the photochemical production and the consumption of $NO_2$ in specific chemical reactions like the ozone formation at the surface.

In order to evaluate the relationship between the $NO_2$ and the $PM_{10}$ levels in the atmosphere and the forest fires the Spearman correlation coefficient was estimated between the pollutant concentration and the area burned and the number of fires. All results are statistically significant at a 0.05 significance level.

### 6.2.2. Air quality modelling

The MM5/CHIMERE was the applied air quality modelling system for reference and future climatic scenario. This numerical system has been widely tested and successfully used over Portugal [Monteiro *et al*., 2005b; Monteiro *et al*., 2007; Monteiro, 2007]. The HadAM3P [Jones *et al*., 2005] simulations for the reference and the IPCC SRES A2 climatic scenario were used to driven the MM5/CHIMERE modelling system. The forest fire emissions for both scenarios were estimated and considered in the air quality simulations over Portugal.

*The MM5/CHIMERE modelling system application*

The air quality modelling application was performed using the chemistry-transport model CHIMERE [Schmidt *et al*., 2001; Bessagnet *et al*., 2004], forced by the mesoscale model MM5 [Grell *et al*., 1994]. The MM5 model has been used worldwide in several regional climate studies [Leung and Ghan, 1999; Boo *et al*., 2004; Leung *et al*., 2004; Van Dijck *et al*., 2005]. CHIMERE has also been applied in climate change impact assessment studies over Europe [Szopa *et al*., 2006].

The Fifth-Generation Penn State University/National Center for Atmospheric Research (PNU/NCAR) Mesoscale Model, known as the MM5, is a nonhydrostatic, vertical sigma-coordinate model designed to simulate mesoscale atmospheric circulations. MM5 has multiple nesting capabilities, availability of four-dimensional data assimilation (FDDA), and a large variety of physics options. The selected MM5 physical options were based on the already performed validation and sensitivity studies over Portugal [Ferreira *et al*., 2004; Aquilina *et al*., 2005; Carvalho *et al*., 2006b] and over the Iberian Peninsula

[Fernandez *et al*., 2007]. Fernandez *et al*. [2007] performed a series of experiments aimed to test the capability of the MM5 in simulating climate conditions over the Iberian Peninsula, through a set of sensititivy experiments including the response to different convective schemes and surface process parameterizations. The MM5 model generated the several meteorological fields required by CHIMERE model, such as wind, temperature, water vapour mixing ratio, cloud liquid water content, 2 m temperature, surface heat and moisture fluxes and precipitation.

CHIMERE is a tri-dimensional chemistry-transport model, based on the integration of the continuity equation for the concentrations of several chemical species in each cell of a given grid. It was developed for simulating gas-phase chemistry [Schmidt *et al*., 2001], aerosol formation, transport, and deposition [Bessagnet *et al*., 2004; Vautard *et al*., 2005] at European and urban scales. The meteorological input variables driven by the MM5 model are linearly interpolated to the CHIMERE grid. In addition to the meteorological input, the CHIMERE model needs boundary and initial conditions, emission data, and the land use and topography characterization. The non-methane volatile organic compounds (NMVOCs) are disaggregated into 227 individual VOCs according to the speciation suggested by Passant [2002] for each activity sector. The methodology for biogenic emissions of isoprene and terpenes is described in Schmidt *et al*. [2001]. The land use database comes from the Global Land Cover Facility [Hansen *et al*., 2000], providing the grid cell coverage of coniferous and broadleaf forests. The Stohl *et al*. [1996] methodology is used for biogenic emissions of nitrogen monoxide (NO) from fertilized soils. The model simulates the concentration of 44 gaseous species and 6 aerosol chemical compounds.

The gas-phase chemistry scheme, derived from the original complete chemical mechanism MELCHIOR [Lattuati, 1997], has been extended to include sulfur aqueous chemistry, secondary organic chemistry and heterogeneous chemistry of HONO and nitrate [Hodzic *et al*., 2005]. The population of aerosol particles is represented by a sectional formulation, assuming discrete aerosol size sections and considering the particles of a given section to be internally mixed. Six diameter bins ranging between 10 nm and 40 μm, with a geometric increase of bin bounds, are used. The aerosol model accounts for both inorganic and organic species, of primary or secondary origin, such as primary particulate matter (PPM), sulfates, nitrates, ammonium, secondary organic species (SOA) and water. PPM is composed of primary anthropogenic species such as elemental and organic carbon, and mineral materials. The CHIMERE model requires hourly spatially resolved emissions for the main anthropogenic gas and aerosol species. For the simulation over Europe, the anthropogenic emissions for $NO_x$, CO, $SO_2$, NMVOC and $NH_3$ gas-phase species, and for $PM_{2.5}$ and $PM_{10}$ are provided by the EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) [Vestreng, 2003] with a spatial resolution of 50 km. The national inventory INERPA was used over the Portugal domain [Monteiro *et al*., 2005b]. This inventory takes into account annual emissions from line sources (streets and highways), area sources (industrial and residential combustion, solvents and others) and large point sources (with available monitoring data at each industrial plant). Time disaggregation was calculated by the application of monthly, weekly, and hourly profiles obtained in the scope of the GENEMIS Project [GENEMIS, 1994].

In the present analysis, the CHIMERE model was applied first at the European scale (with 50 x 50 $km^2$ resolution) and then over Portugal using the same physics and a simple one-way nesting technique, with 10 x 10 $km^2$ horizontal resolution. The vertical resolution consists of eight vertical layers of various thicknesses extending from ground to 500 hPa, with the first layer at 50 m. Lateral and top boundaries for the large-scale run were obtained from the LMDz-INCA (gas species) [Hauglustaine *et al*., 2004] and GOCART (aerosols) [Ginoux *et al.*, 2001] global chemistry transport models. Transport of Saharan dust from the GOCART boundary conditions, as well as within-domain erosion, are considered using the formulation of Vautard *et al*. [2005]. For the Portugal domain, boundary conditions are provided by the European scale simulation. The MM5/CHIMERE simulation characteristics are exhibited in Table 6.1.

Table 6.1 – MM5 and CHIMERE simulation definitions.

| | | European domain (D1) | Portuguese domain (D2) |
|---|---|---|---|
| MM5 | Dimensions (X,Y) | 96 x 81 cells | 73 x 109 cells |
| | Horizontal resolution | 54 km | 9 km |
| | Vertical resolution | 25 sigma levels | 25 sigma levels |
| | Physics | MRF PBL scheme | MRF PBL scheme |
| | | RRTM radiation scheme | RRTM radiation scheme |
| | | Grell cumulus scheme | Grell cumulus scheme |
| | | Simple ice moisture scheme | Graupel moisture scheme |
| CHIMERE | Dimensions (X,Y) | 47 x 79 cells | 29 x 58 cells |
| | Horizontal resolution | 50 km | 10 km |
| | Vertical resolution | 8 levels | 8 levels |
| | Chemical mechanism | Melchior | Melchior |

In order to simulate the impact of climate change on air quality the MM5/CHIMERE modelling system was forced by the Hadley Centre global atmospheric circulation model HadAM3P [Jones *et al*., 2005]. The Hadley Centre's HadAM3P (2.5º latitude by 2.5º longitude resolution) is a successor version of the HadAM3H model [Pope *et al*., 2000; Jones *et al*., 2001], that is an improved version of the atmospheric component of the latest Hadley Centre coupled Atmosphere-Ocean General Circulation Model (AOGCM), HadCM3 [Gordon *et al*., 2000]. The sea surface temperatures (SSTs) used in the HadAM3P reference simulation were taken from a gridded data set of monthly mean observations covering the period 1960-1990 [Jones *et al*., 2003]. The climate change simulation used SSTs from an existing HadCM3 simulation applying the obtained monthly anomalies to the 30 year averaged gridded monthly mean observed climatology. The HadAM3P simulations for reference and future climatic scenarios are freely available through the Met Office Hadley Centre, United Kingdom.

Reference (1990) and the IPCC SRES-A2 climatic scenario (2100) over Europe and over Portugal were simulated by dynamical downscalling using the outputs of HadAM3P, as initial and boundary conditions to the MM5 model (Figure 6.3). The MM5 model requires initial and time evolving boundary conditions for wind components, temperature, geopotential height, relative humidity and surface pressure. MM5 also requires the specification of SSTs.

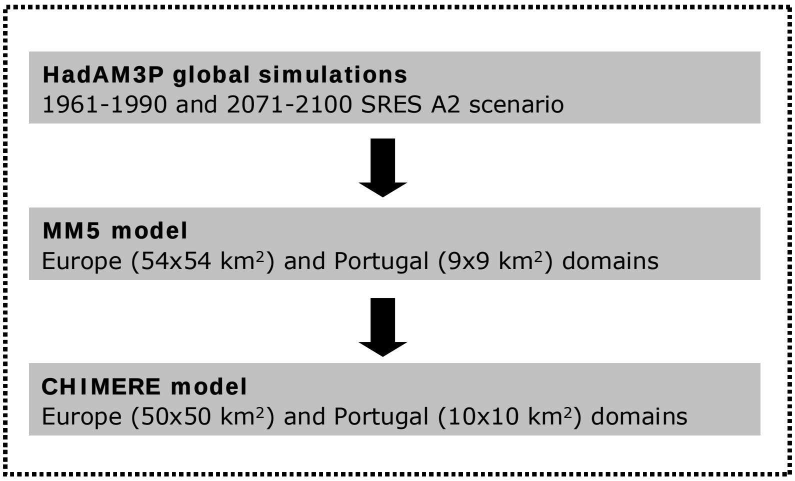



Figure 6.3 – Flowchart of the air quality modelling application.

The integration between the HadAM3P outputs and the MM5 model was set through a programming stage that was implemented in order to convert, interpolate and generate the pressure levels and the data formats requirements needed for the MM5 simulations. The downscalling of the HadAM3 model outputs to the MM5 model has already been carried out for the regional climate change simulations over South America [Solman *et al*., 2007].

To better evaluate the influence of the future fire activity on air quality, the anthropogenic emissions were kept constant in the simulations for the 2100 scenario. The emissions were not scaled in accordance to the IPCC SRES A2 scenario. The air quality simulations assumed no changes in regional anthropogenic emissions of the chemical species primarily involved in the chemical reactions of ozone formation and destruction, but only accounted for changes in the climate. This idealized regional model simulation provides insights into the contribution of possible future climate changes on ozone and particulate matter concentrations. The forest fire emissions were just included in the simulation over Portugal. The European domain simulation did not take into account these emissions.

The MM5/CHIMERE simulations were conducted from May 1$^{st}$ to October 30$^{th}$ for 1990 and 2100. Over Portugal the simulation design comprised three approaches:

- Control simulation (C1) – 1990 climate and 1990 forest fire emissions;
- Scenario 1 (S1) – 2100 climate and 1990 forest fire emissions;
- Scenario 2 (S2) – 2100 climate and 2100 forest fire emissions.

In this sense and in order to assess the impact on air quality it is possible to analyse the changes only due to climate change and the impact of both climate change and future forest fire emissions.

### *Forest fire emissions estimation*

Forest fire emissions depend on multiple and interdependent factors like forest fuels characteristics, burning efficiency, burning phase, fire type, meteorology, and geographical location.

Fuel type and load are one of the most important factors affecting fire emissions. Variations in fuel characteristics and consumption may contribute to uncertainties of 30 % in estimates of wildfires emissions [Peterson, 1987; Peterson and Sandberg, 1988]. This is a critical factor when describing forest fuels because available fuel mass depends on the location, fuel type and time of the year.

Burning efficiency is also a significant fire emissions parameter, which is usually defined as the ratio of carbon released as $CO_2$ to total carbon present in the fuel. In laboratorial and field experiments, the burning efficiency can be expressed as the fraction burned related to the total biomass available. Models to estimate forest fire emissions are frequently based on emission factors, burning efficiency, fuel loads and area burned. Generically, emissions can be estimated through the Equation 6.1:

$$E_i = A \times B \times \beta \times EF_i \tag{6.1}$$

where, $E_i$ – compound i emissions [g]; A – area burned [$m^2$]; B – fuel load [kg $m^{-2}$]; β – global burning efficiency; $EF_i$ – compound i emission factor [g $kg^{-1}$].

The selected fuel load, combustion efficiency and emission factors for CO, $CH_4$, $PM_{10}$, $PM_{2.5}$, non-methane hydrocarbons (NMHC) and $NO_x$ are the most adequate for the Portuguese land use types (Table 6.2). This data was gathered under the scope of the European Commission SPREAD Project - Forest Fire Spread Prevention and Mitigation [Miranda *et al.*, 2004; Miranda *et al.*, 2005c] and the Gestosa experimental field fires [Viegas *et al*., 2002].

Table 6.2 - Fuel load, combustion efficiency and emission factors suitable for Portuguese forest and shrub characteristics [Miranda *et al.*, 2004; Miranda *et al.*, 2005c].

| **Fuel** | **Fuel load (kg $m^{-2}$)** | **Combustion efficiency** | **Emission factor (g $kg^{-1}$)** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | **$CO_2$** | **CO** | **$CH_4$** | **NMHC** | **$PM_{2.5}$** | **$PM_{10}$** | **$NO_x$** |
| Shrub | 1.00 | 0.80 | 1477 | 82 | 4 | 9 | 9 | 10 | 7 |
| Resinous | 8.60 | 0.25 | 1627 | 75 | 6 | 5 | 10 | 10 | 4 |
| Deciduous | 1.75 | 0.25 | 1393 | 128 | 6 | 6 | 11 | 13 | 3 |
| Eucalyptus | 3.90 | 0.25 | 1414 | 117 | 6 | 7 | 11 | 13 | 4 |

Firstly the ratio between the area burned in forest stands and shrubs has been estimated based on the 1980-1990 fire activity records at district level. These ratios were kept constant for the forest fire emissions estimation under future climate. Based on the national forestry inventory [DGRF, 2006a] the forest stands percentage of resinous, deciduous and eucalyptus by district was also considered.

The annual forest fire emissions were estimated for 1990 and for 2100 climates and then included in the CHIMERE model application over Portugal. The annual forest fire emissions were uniformly distributed by district in accordance to the annual average area burned observed in 1980-1990 and projected for the 2071-2100 period. Monthly and hourly profiles of forest fire activity were considered in the emissions temporal disaggregation. For the reference simulation, the monthly profiles were estimated based on the monthly area burned registered between 1980 and 1990 in Portugal. The monthly area burned estimates between 2071 and 2100 (Appendix D) were used to calculate the monthly profiles under the IPCC SRES A2 scenario (Table 6.3).

Table 6.3 – Monthly distribution of the area burned for both climatic scenarios used to distribute the annual forest fire emissions.

| Month | 1980 – 1990 (%) | 2071 - 2100 (%) |
|---|---|---|
| 1 | 0.2 | 0.0 |
| 2 | 0.2 | 0.1 |
| 3 | 0.3 | 0.2 |
| 4 | 0.4 | 0.4 |
| 5 | 0.4 | 2.6 |
| 6 | 2.7 | 12.5 |
| 7 | 28.3 | 35.2 |
| 8 | 34.9 | 34.4 |
| 9 | 28.8 | 13.0 |
| 10 | 3.8 | 1.4 |
| 11 | 0.1 | 0.2 |
| 12 | 0.0 | 0.0 |

Some studies suggest that biomass burning exhibits a pronounced diurnal cycle with peak emissions during the afternoon and very low emissions during the night [Eck *et al*., 2003; WRAP, 2005]. The hourly smoke emissions (Table 6.4) were estimated using the WRAP diurnal profiles [WRAP, 2005]. Table 6.4 consists of a percent of fuel consumed for each hour of the day. It is important to note that it was not considered any differentiation among working days and weekends since no reliable information was gathered for forest fire activity on this subject.

Table 6.4 – Diurnal distribution of fuel consumption used to distribute forest fire emissions [WRAP, 2005]

| Hour | % per hour | Hour | % per hour |
|---|---|---|---|
| 1 | 0.57 | 13 | 10.0 |
| 2 | 0.57 | 14 | 13.0 |
| 3 | 0.57 | 15 | 16.0 |
| 4 | 0.57 | 16 | 17.0 |
| 5 | 0.57 | 17 | 12.0 |
| 6 | 0.57 | 18 | 7.00 |
| 7 | 0.57 | 19 | 4.00 |
| 8 | 0.57 | 20 | 0.57 |
| 9 | 0.57 | 21 | 0.57 |
| 10 | 2.00 | 22 | 0.57 |
| 11 | 4.00 | 23 | 0.57 |
| 12 | 7.00 | 24 | 0.57 |

According to the WRAP [2005] analysis the daily emissions peak is attained at 16 LST and the minimum values are registered during the night. To estimate the hourly forest fire emissions the same diurnal profile was applied for reference and future scenario.

It is important to stress that the diurnal distribution of the forest fire emissions is based on the fuel consumption data registered for forest fires events in USA. This type of information is still reduced for Portuguese forest fires. Although, data gathered for forest fires events suggests that the peak ignitions occurs between 14 and 17 LST [DGRF, 2007].

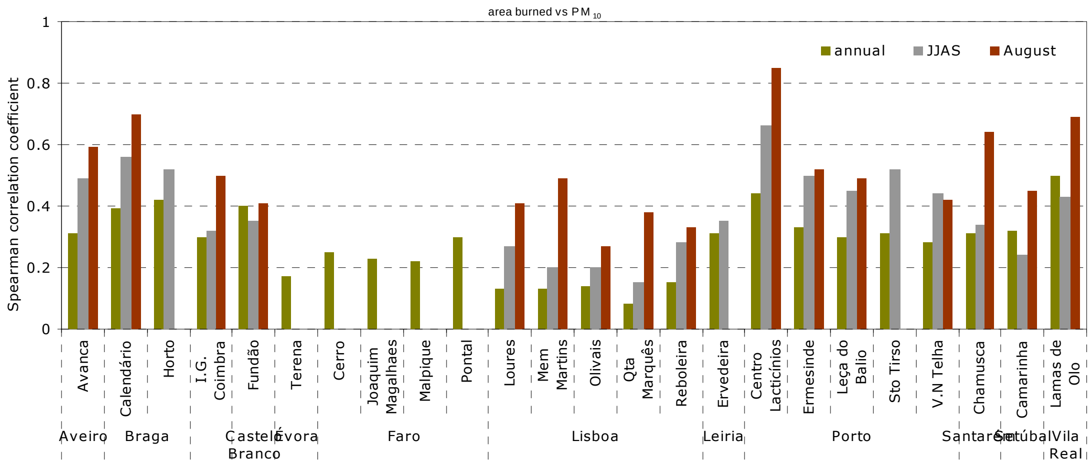
## 6.3. Results and Discussion

In this section the correlation analysis between the forest fire activity and the atmospheric pollutants concentrations is discussed - *Relationship between forest fires and atmospheric polluttants.* The forest fire emissions estimation for the reference and future climatic scenario is presented and analysed - *Forest fire emissions in a future climatic scenario*. Finally, the impacts of climate change and forest fire emissions on air quality addressed through air quality modelling are discussed - *Air quality impacts assessment*.

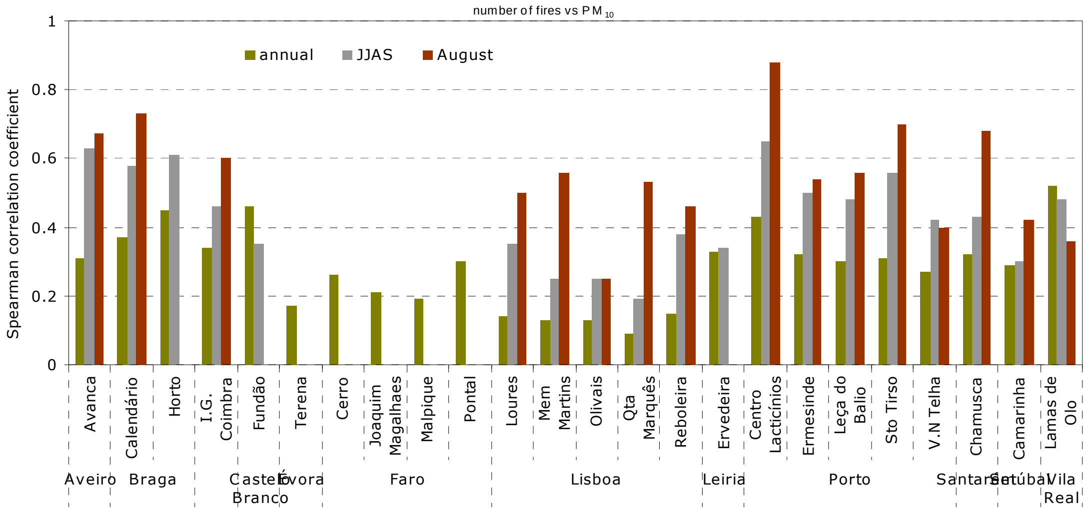
### 6.3.1. Relationship between forest fires and atmospheric pollutants

The SAS program version 9.1.3 was used to estimate the Spearman correlation coefficients between the $PM_{10}$ and $NO_2$ concentrations and the area burned and the number of fires between 1995 and 2005. All results are statistically significant at a

0.05 significance level. Figure 6.4 and Figure 6.5 presents the obtained Spearman coefficients for $PM_{10}$ and $NO_2$, respectively, by station and for the analysed time periods. The stations not presenting any value for a specific time period indicates that the obtained results were not statistically significant.




a)




b)

Figure 6.4 - Spearman coefficient between the daily average $PM_{10}$ concentration, and the area burned a) and the number of fires b), by station, for the 1995-2005 period.

The best correlations for the $PM_{10}$ daily average were obtained for the number of fires and for August (Figure 6.4). All stations, except Lamas de Olo, in Vila Real district, exhibit an increase in the Spearman coefficients from the annual basis to the month of August. The districts of Porto, Braga, and Aveiro present the highest correlation coefficients between the $PM_{10}$ daily average and the number of fires. From 1995 to

2005, Porto district registered the highest number of forest fire occurrences accounting for 22 % of the total, followed by Braga with 14 % and Aveiro 7 %. The highest Spearman coefficients were obtained in August at Centro de Lacticínios (0.88), Calendário (0.71), Santo Tirso (0.70) and Chamusca (0.68) stations. It should be noted that the data availability at these stations (Figure 6.2) is reduced from one to three years maximum. The relationship between $PM_{10}$ daily average and area burned is not as high. The best correlations were also obtained for the month of August and the maximum value was attained at Centro de Lacticínios (0.85) station in Porto district.

Figure 6.5 presents the correlation coefficients between the area burned and the number of fires and the $NO_2$ levels in the atmosphere. The analysis for the $NO_2$ daily maximum concentrations revealed that the obtained correlations were lower than for the $PM_{10}$ analysis.

The analysis based on the annual data showed that all the stations located in the Lisbon district presented a negative correlation with the area burned and the number of fires. In addition, the majority of the stations did not present statistically significant correlations for the summer period. In Lisbon district most of the analysed stations were classified as urban background. The large amount of $NO_x$ emissions released from traffic is clearly influencing the correlations on the annual basis. The highest correlation factors were obtained in August reaching almost 0.60 in the districts of Aveiro, Braga, and Coimbra. Lamas de Olo station, located in the Vila Real district, is a good indicator of the influence of forest fire emissions in the rural background environment. It is possible to see a clear increase on the correlation coefficients obtained for the annual, JJAS and August periods. This station registered the highest Spearman correlation (0.68) between the area burned and the $NO_2$ maximum concentrations. The correlations obtained for the area burned and number of fires do not differ significantly.

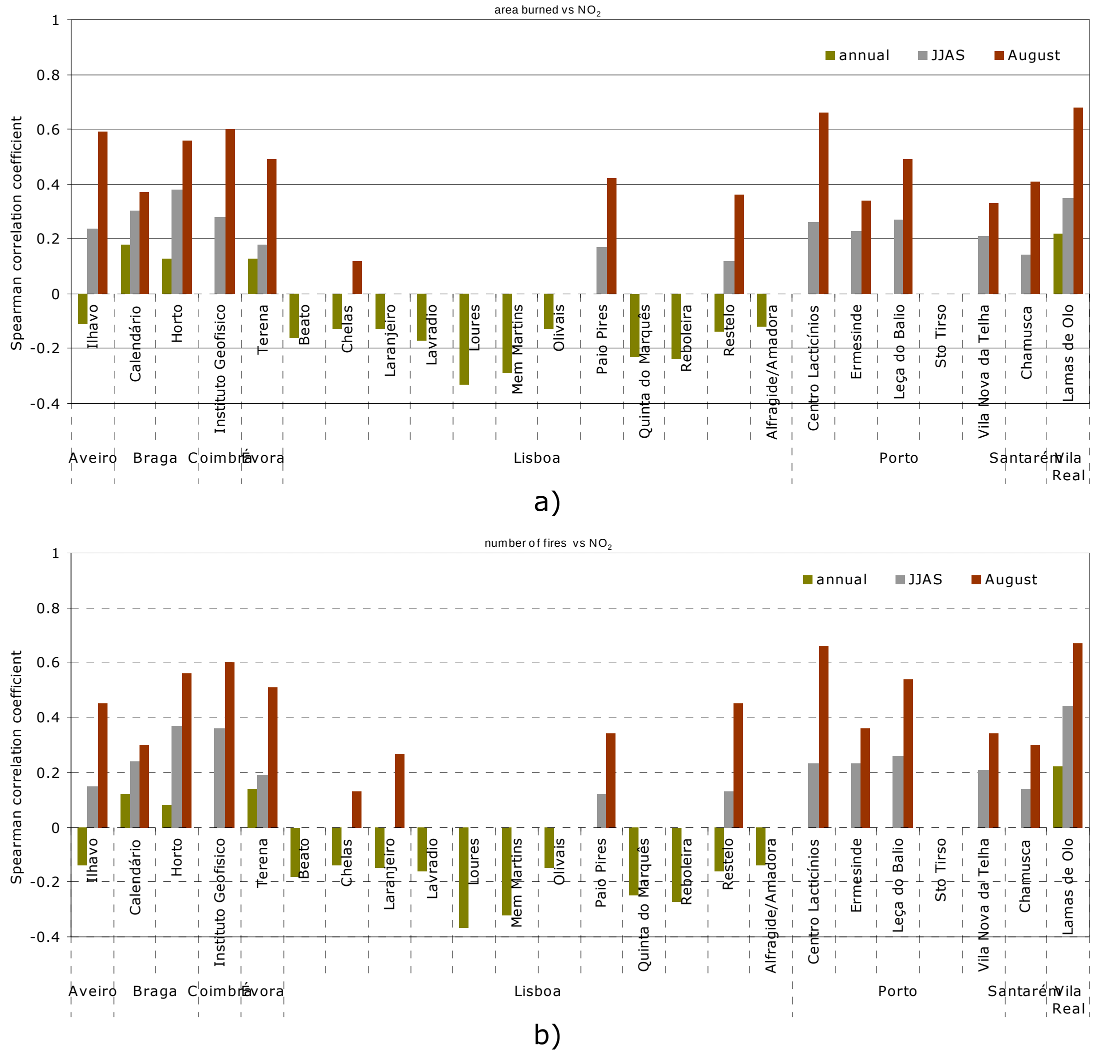



Figure 6.5 - Spearman coefficient between the daily maximum $NO_2$ concentrations, and the area burned a) and the number of fires b), by station, for the 1995-2005 period.

The performed correlation analysis revealed that for both studied pollutants the best correlations were obtained for the month of August. This should be mainly related to the fact that the forest fire activity is highest in this month. The month of August accounted for 53 % and 30 % of the total area burned and the number of fires, respectively, registered between 1995 and 2005.

The obtained results point to statistically significant correlations between fire activity in Portugal and $PM_{10}$ and $NO_2$ levels in the atmosphere. $PM_{10}$ levels presented higher correlations with the forest fires in Portugal and this is an important outcome of the performed analysis. $PM_{10}$ are a good indicator of forest fires impact on air quality over Portugal.

### 6.3.2. Forest fire emissions in a future climatic scenario

Forest fire emissions estimation, for reference and future scenario, was based on the annual area burned presented in Table 5.3 (§5.3.1, pp 102) and on data exhibited in Table 6.2.

Table 6.5 shows the comparison between forest fire emissions and the industry and transport emissions for the year 1990.

Table 6.5 - Comparison between anthropogenic and forest fire emissions (Gg) for the year 1990.

| **Source** | **$CO_2$** | **CO** | **$CH_4$** | **NMHC** | **$PM_{2.5}$** | **$PM_{10}$** | **$NO_x$** |
|---|---|---|---|---|---|---|---|
| Forest fires | 1007.4 | 62.4 | 3.7 | 4.4 | 6.8 | 7.4 | 3.1 |
| Industry | 33513.4 | 69.2 | 23.9 | 147.2 | 35.5 | 51.2 | 111.0 |
| Transport | 9827.7 | 511.0 | 3.5 | 118.1 | 8.5 | 8.5 | 111.7 |
| Forest fires/total (%) | 2.3 | 9.7 | 11.9 | 1.6 | 13.4 | 11.1 | 1.4 |

Forest fires may represent a considerable percentage of the total emissions, reaching up to 11.9 % for $CH_4$ and 13.4 % for $PM_{2.5}$. Miranda *et al*. [2007] concluded that in the year 2003 because of the severe area burned the forest fire emissions accounted for 40 % of the CO and $CH_4$ total emissions.

Figure 6.6 presents the estimated emissions for both scenarios. All districts suffer a substantial increase in emissions due to the projected raises on the area burned [Carvalho *et al*., 2007c]. This increase on the forest fire emissions is proportional to the area burned projections discussed in Chapter 5.

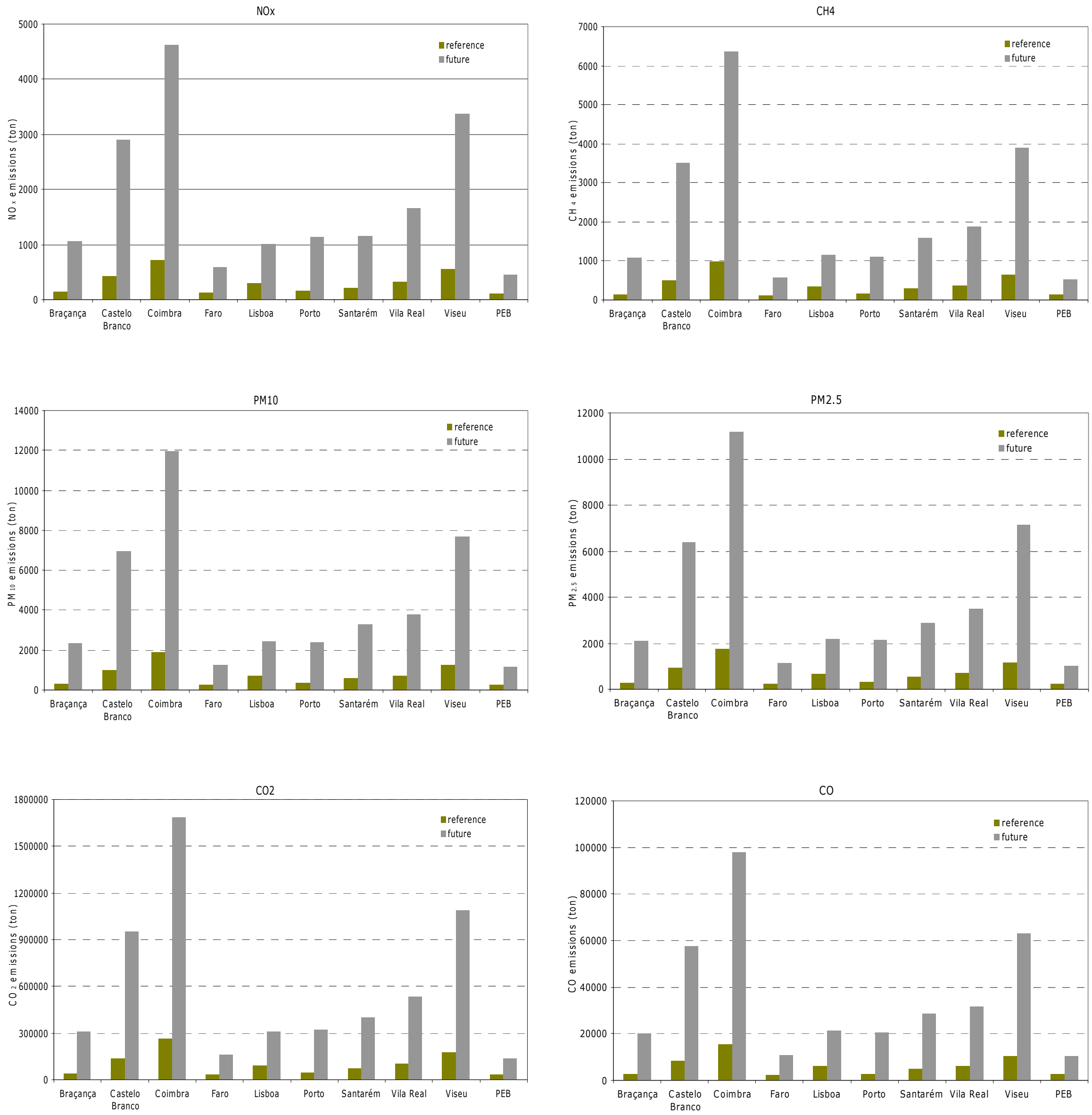



Figure 6.6 – Annual forest fire emissions (ton), by district, for reference and future climate.

All analysed pollutants present increases in its emissions leading to the greenhouse gases enhancement in the atmosphere. CO, $CO_2$, and $CH_4$ emissions were converted into $CO_2$ equivalent emissions based on the global warming potential (GWP) for a 100 years' time horizon [IPCC, 1995] (Figure 6.7).

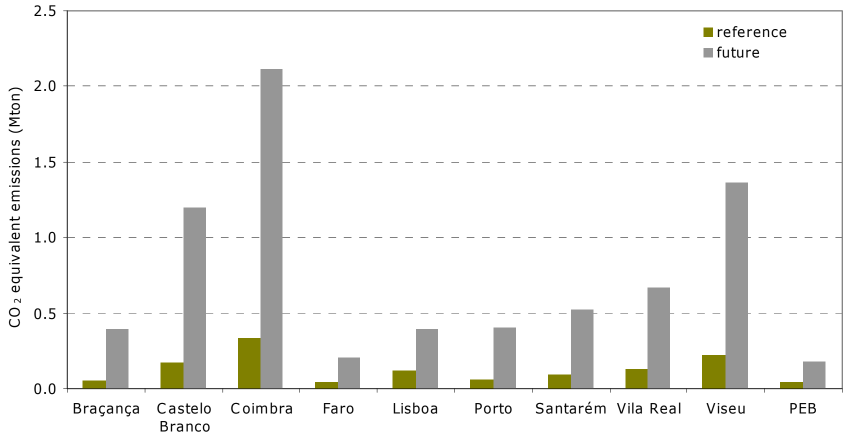



Figure 6.7 - $CO_2$ equivalent emissions (Mton), by district, for reference and future climate.

The annual $CO_2$ equivalent emissions derived from forest fires account for 1.27 Mton for the 1980-1990 period and 7.44 Mton in a 2 x $CO_2$ scenario. This represents an overall increase of approximately 500 %.

The GHGs inventory that each EU Member State has to submit to the United Nations Framework Convention on Climate Change (UNFCCC) refers to six categories: energy, industrial processes, solvent and other product use, agriculture, land-use change and forestry (LUCF) and waste. According to the IPCC [2000], the LUCF category considers good practice to estimate $CO_2$ and non-$CO_2$ emissions from biomass burning on managed forestland. According to this methodology, in a large period of time (20 years) the net $CO_2$ flux may be zero, if the disturbed areas are reforested and the sink capacity restored. In a shorter time period, the carbon release is not immediately recaptured by the forest re-growth, and the uptake of the quantity of carbon released in a fire by the forest re-growth may take several years. Such an estimate implies a better knowledge of the average carbon stocks and the evolution in time of the damaged areas. In this scope, the emissions from forest fires are still poorly accounted in the national inventories and this may represent a considerable error. Estimates of $CO_2$ equivalent emissions from LUCF show that this category was a net emitter in 1990 (3.8 Mton) and a carbon sink in 2004 (-2.5 Mton). The situation was temporarily inverted in 2003, when this source appeared as a net emitter (8.2 Mton) [Ferreira *et al*., 2006].

### 6.3.3. Air quality impacts assessment

As described previously the global model HadAM3P outputs were used to set the initial and boundary conditions for the MM5 simulations for reference (1990) and for the IPCC SRES A2 scenario (2100).

Anagnostopoulou *et al*. [2008] analysed the performance of the HadAM3P simulations against the NCEP/NCAR reanalysis data [Kalnay *et al*., 1996] over the Mediterranean region. The authors concluded that the HadAM3P accurately reproduces seasonal 500 hPa geopotential heights, whereas their seasonal variability is underestimated. The 500 hPa height reflects a broad range of meteorological influences on air quality. The frequency of occurrence of fourteen weather types has been assessed over Greece. The results indicate that the HadAM3P is able to capture the mean patterns of the circulation types. The obtained results give some confidence to use the HadAM3P outputs as initial and boundary conditions for regional simulations. In the scope of an air quality assessment it is important that the GCM gives an accurate representation of the large-scale flow fields for the region of interest.

Solman *et al*. [2007] applied the MM5 model over southern South America for climate change impact studies. The dynamical downscalling of the HadAM3H outputs to the MM5 model were assessed for present-day climate (1981-1990). The MM5 model performance was evaluated in terms of seasonal means, seasonal cycles, interannual variability, and extreme events. The authors concluded that the observed regional patterns of surface air temperatures (means, maxima, and minima) were well reproduced. The broad spatial pattern of precipitation and its seasonal evolution was also well captured by the model. Extremes of precipitation were better reproduced by the regional model compared with the driving model. Overall, it was concluded that the MM5 model is capable of reproducing the main regional patterns and seasonal cycle of the surface variables.

Before analysing the impacts of future climate on air quality, namely on $O_3$ and $PM_{10}$ levels, the analysis of the MM5 reference climate simulation over Portugal was performed for 1990. The 1990 daily MM5 outputs between May 1$^{st}$ and October 30$^{th}$ were compared against the data monitored at 12 meteorological stations covering the majority of the Portuguese territory giving an indication of the MM5 performance over each specific region. These are the same stations used in the statistical analysis performed in Chapter 3 and in the validation of the regional climate model HIRHAM presented in Chapter 4.

The performed statistical measures were the root mean square error (RMSE) and the BIAS. These two measures present an indication on how well the model simulates the observed meteorological fields. The RMSE gives information about the absolute errors obtained within the observed-predicted pairs of results. The BIAS gives an indication about the overprediction or the underprediction of the analysed variables [Borrego *et al.*, 2008]. The RMSE and the BIAS expressions are presented in Equations 6.2 and 6.3, respectively.

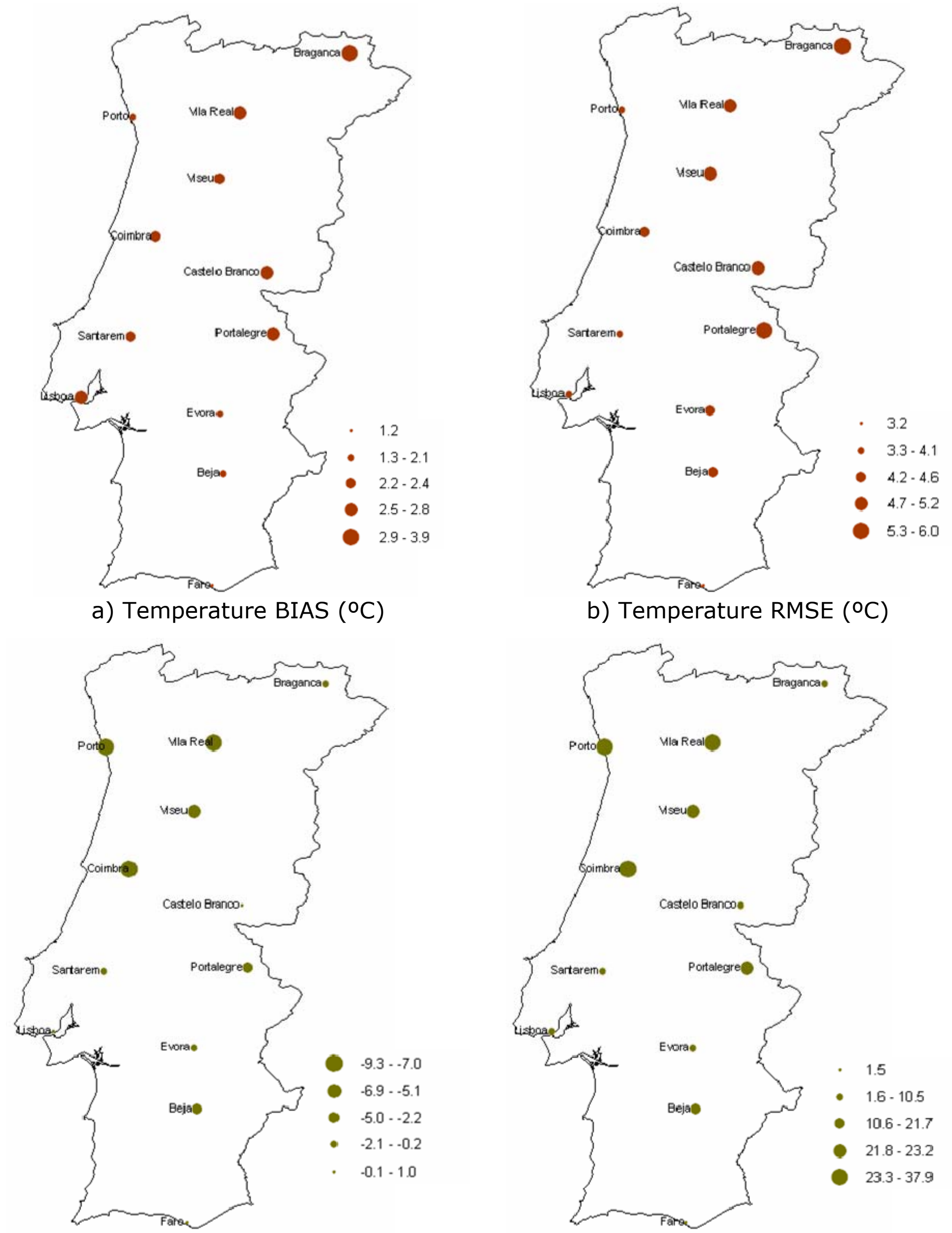
$$RMSE = \sqrt{\frac{1}{N}\sum_{i}^{N}(O_i - M_i)^2} \qquad (6.2)$$

$$BIAS = \frac{1}{N}\sum_{i}^{N}(O_i - M_i) \qquad (6.3)$$

where $N$ is the total number of data, $O_i$ the observed value and $M_i$ the correspondent simulated value.

Figure 6.8 exhibits the RMSE and the BIAS for the daily average temperature and daily precipitation at the 12 meteorological stations over Portugal in 1990 between May 1$^{st}$ and October 30$^{th}$.

The MM5 model exhibits a clear underestimation of the mean daily temperature in all analysed stations especially in the inner regions of the north and centre of Portugal (Bragança, Vila Real, Castelo Branco, and Portalegre). The highest difference was attained in Bragança reaching almost 4 ºC. The same behaviour has already been detected by Monteiro [2007] but for different simulation periods. The RMSE is higher in the inner regions of the country with values close to 6 ºC. The precipitation tends to be overestimated by the MM5 model namely in the north and centre (Porto, Vila Real, and Coimbra). The RMSE for the daily precipitation varies from 1.5 to 38 mm. The rain amount frequency at Porto, Vila Real, and Coimbra shows that the MM5 model tends to overestimate the number of days with high precipitation (not shown). The model also shows a decrease in the number of rain free days. This behaviour has already been detected by Gustafson and Leung [2007] for dowscalled simulations over the United States. These deviations can be closely related to the applied spatial resolution being insufficient to correctly define topography and land use especially over the regions of complex terrain and with the land-sea interaction. The selected cumulus scheme may also contribute to these differences.




a) Temperature BIAS (ºC)

b) Temperature RMSE (ºC)

c) Precipitation BIAS (mm)

d) Precipitation RMSE (mm)

Figure 6.8 - MM5 validation over Portugal concerning the BIAS (a, c) and the RMSE (b, d) for daily mean temperature (a, b) and daily precipitation (c, d) between May 1st and October 30th of 1990.

This is a very simple analysis of the MM5 performance over Portugal for the 1990 climate. It is not expected that the MM5 model application in a climatic analysis gives an exact response of the 1990 climate on a daily basis but the average conditions, namely seasonal, and variability should be well represented by the model. The reduced number of performed simulations limits this kind of assessment.

Even if the dowscalled results are not completely accurate, the necessity of using the regional downscalling approach is clear. With the strong dependency on localized flow patterns, air quality models need the higher-resolution wind, temperature, precipitation, and boundary layer structure produced by regional models [Gustafson and Leung, 2007].

Concerning CHIMERE it was not possible to compare the air quality data simulated from May to October of 1990 due to lack of monitored air pollutants in the majority of the country [Carvalho, 2006]. Nevertheless, confidence on CHIMERE results exists since it has been applied over Portugal for several years from 2001 to 2006 and the obtained concentrations fields are in good agreement with observations [Monteiro *et al*., 2005b; Monteiro *et al*., 2007; Monteiro, 2007].

In this study the air quality impacts assessment is performed for both simulated domains, Europe and Portugal. The climate change and the forest fire emissions influence on air quality are assessed and discussed. Figure 6.9 shows the MM5/CHIMERE results regarding the monthly mean of surface $O_3$ changes from May to October between the 2100 climate and 1990 climate over Europe. Since the anthropogenic emissions have not been scaled in accordance to the SRES A2 scenario, the obtained changes in $O_3$ surface levels are only due to climate change forcing. The monthly averaged MM5 outputs (boundary layer height, wind speed, relative humidity and temperature) over Europe for both climates are collected in Appendix E.

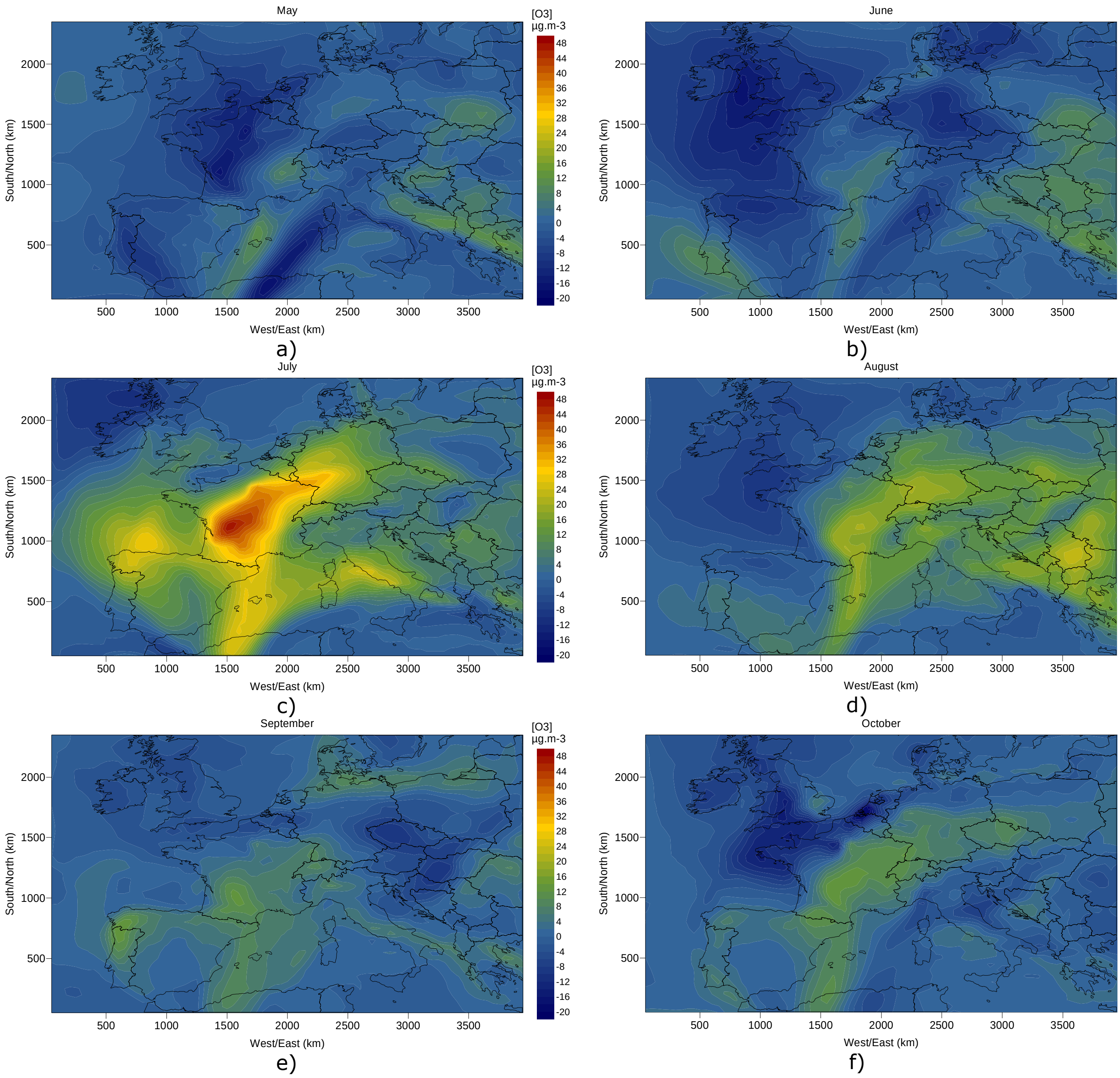



Figure 6.9 - Monthly mean surface $O_3$ changes simulated over Europe with MM5/CHIMERE modelling system between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

The obtained modelling results show that the highest changes are observed over central Europe registering $O_3$ increases of almost 48 µg $m^{-3}$ (~24 ppb) in July. Over the ocean, where the destruction due to water vapour prevails, $O_3$ decreases by up to 22 µg $m^{-3}$. These results are in the same range of magnitude of those found by Hauglustine *et al*. [2005]. According to Dentener *et al*. [2006], climate-driven increases in temperature and water vapour tend to decrease surface $O_3$ in the cleanest regions but tend to increase $O_3$ in more polluted areas.

In July it is possible to detect an increase of the $O_3$ levels of approximately 20 μg $m^{-3}$ just over Galicia and the Gulf of Biscay influencing the concentrations of this pollutant in the north of Portugal. This pattern may be explained by the fact that in July the largest temperature increases are over Galicia, France and north United Kingdom (UK). The enhancement on the temperature field is higher in July than in August for this region. Overall the ozone production increases with increased temperature [Sillman and Samson, 1995]. The decrease on the average boundary layer (BL) height and on the average wind speed in July may also contribute to the ozone enhancements over this region (Appendix E). It should also be noted that under a changing climatic scenario there is an average channelling effect from north and central Europe towards the Gulf of Biscay (not shown). In addition, the EMEP emissions grid present high levels of pollutants emitted in Galicia due mainly to industrial combustion processes that in a changing climatic scenario may deeply impact the air quality in the region.

Meteorological conditions appear to have a greatest impact on daily variations in air quality. Some studies have indicated that ozone is strongly positively correlated with high temperatures and solar radiation, as this enhances the photochemical conditions that lead the ozone formation [Comrie, 1996]. In the eastern United States high temperatures, large concentrations of water vapour, high solar radiation and stagnant conditions were the variables mostly correlated with high ozone levels [Vukovich and Sherwell, 2003]. In the southwest United States temperature and mixing height most strongly influence ozone conditions [Wise and Comrie, 2005].

According to Gustafson and Leung [2007] if the BL height is too high in the reference climate run, primary pollutants will be diluted and react under conditions with lower concentrations. If synoptic changes in the future scenario lead to altered BL heights, then the concentrations would change as well. However the nonlinearity of the reactions generating the ozone will produce a different amount of ozone leading to changes other than just the percentage change in the BL height. Kunkel *et al*. [2007] reported that for the northeast USA the mean and the 8-h maximum ozone increase in future climate are due to higher temperatures, lower cloudiness and higher biogenic emissions.

Figure 6.10 exhibits the monthly mean $O_3$ changes over Portugal due to climate change alone and to climate change and future forest fire emissions for July, August and September.

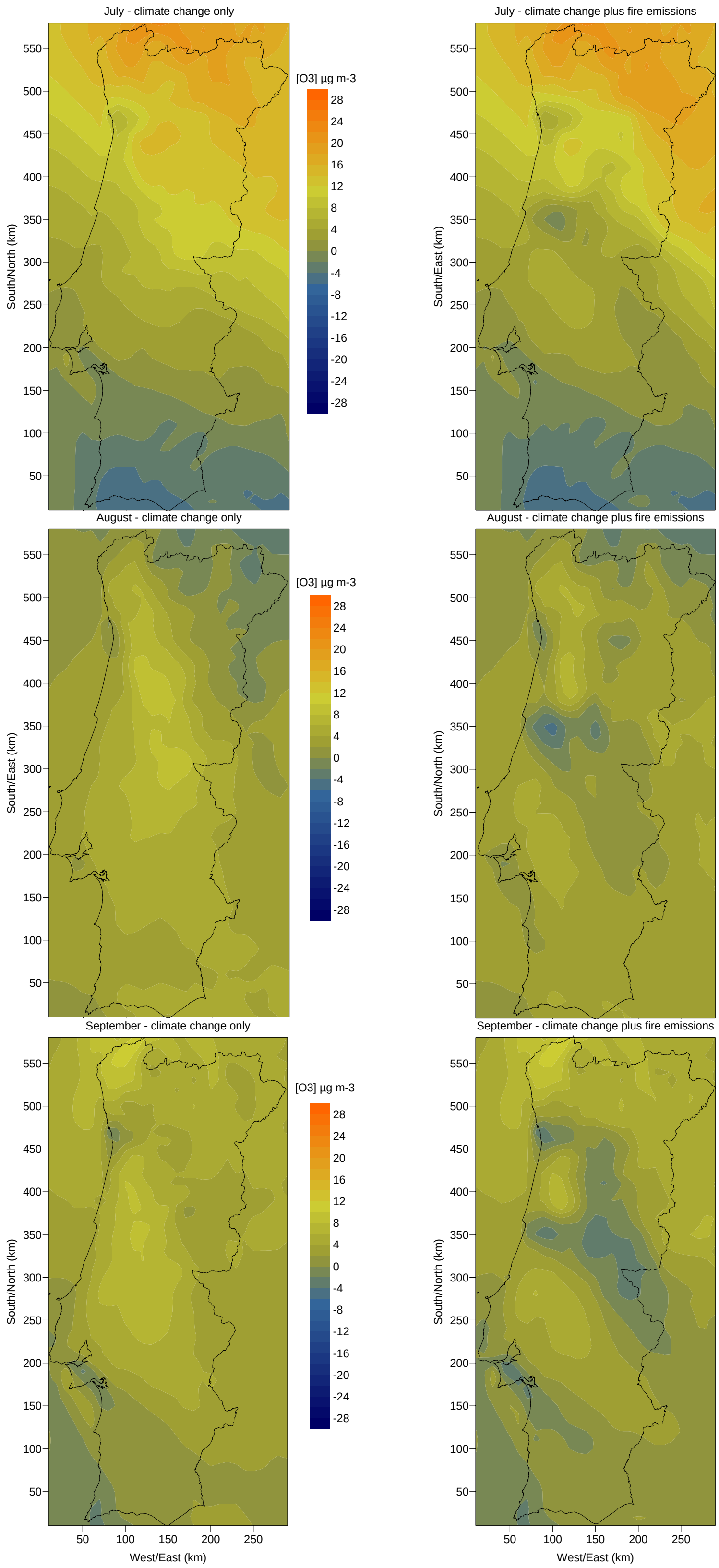



Figure 6.10 – Monthly mean surface $O_3$ changes simulated over Portugal considering only climate change (S1 – C1) and climate change and future fire emissions (S2 – C1) for July, August, and September.

The maps for May, June, and October are collected in Appendix F. The $O_3$ levels are exhibited as differences between future and reference scenarios (S1-C1 and S2-C1).

The highest increase in $O_3$ concentrations are detected in July but this is clearly influenced by the air quality boundary conditions settled in the north of Portugal by the European domain (see Figure 6.9c). In July there is an increase of approximately 20 $\mu g\ m^{-3}$ in the $O_3$ levels in the north and central region of Portugal only due to climate change. If future forest fire emissions are considered the regions in the centre of Portugal especially over Coimbra and Porto in the north experience a smaller increase or even a reduction in the $O_3$ concentrations (-1.2 $\mu g\ m^{-3}$ in July, -4.9 $\mu g\ m^{-3}$ in August and -3.8 $\mu g\ m^{-3}$ in September). This feature is probably due to the $O_3$ consumption promoted by the $O_3$ precursor's emissions released by the forest fires in these regions.

The previous chapter pointed the district of Coimbra as the main affected in terms of future area burned projections. Consequently the future forest fire emissions are highest in this region. The $O_3$ precursor's emissions may also lead to its depletion (e.g. through NO titration) and the overall balance may conduct to the diminishing of the $O_3$ levels in the atmosphere [Seinfeld and Pandis, 1998]. It is also expectable an increase of the $O_3$ concentrations downwind of the fire due to the dispersion of the emitted pollutants and their chemical transformation [Stich *et al*., 2007]. In Figure 6.10 it is possible to see the depletion of the $O_3$ levels in July, August, and September, although the monthly average analysis does not allow verifying a clear increase of the $O_3$ concentrations downwind of the fire locations.

The ozone levels in the atmosphere present a markedly daily profile closely connected to the photochemical activity that reaches its maximum during the afternoon. In this sense and in order to make a more detailed discussion on the $O_3$ concentrations change along the diurnal cycle the $O_3$ average values at 12, 15 and 18 UTC were computed for August (Figure 6.11). The $O_3$ average values at 9 and 21 UTC can be found in Appendix F.

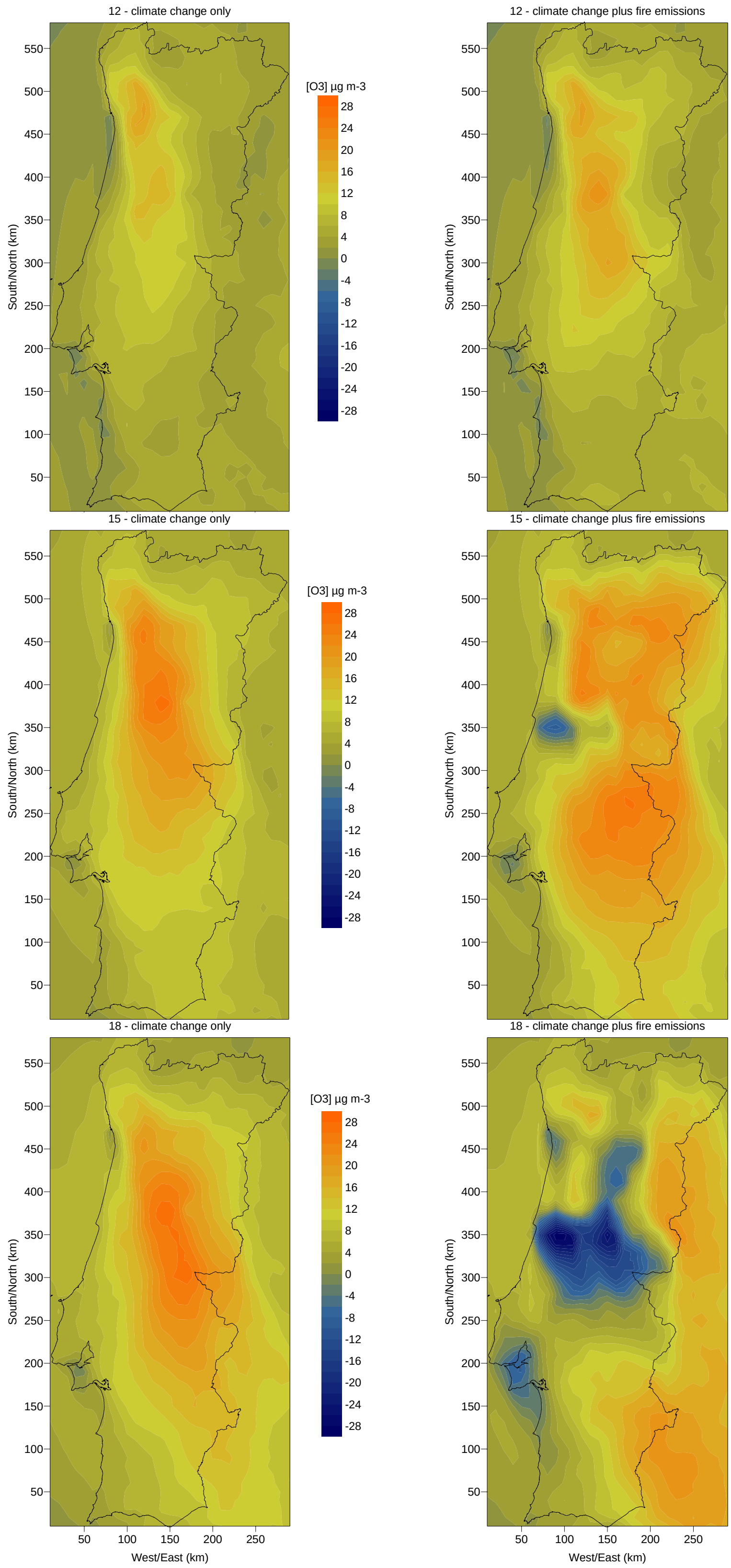



Figure 6.11 - Hourly average $O_3$ concentrations for August at 12, 15 and 18 UTC considering climate change only (S1-C1) and climate change and future forest fire emissions (S2-C1).

During the morning, namely at 9 UTC the $O_3$ levels in the atmosphere are still very low. At this time of the day, there is not a clear trend on the $O_3$ concentrations in the analysed scenarios (Appendix F). At noon, the highest $O_3$ level is observed for the S2 scenario reaching 108 μg $m^{-3}$ in the inner part of the country (not shown). Considering the climate change impacts only, it is possible to see an increase of the $O_3$ concentrations and its plume extension in the districts of Porto and Coimbra.

The highest levels of ozone in the atmosphere are observed at 15 UTC, reaching almost 130 μg $m^{-3}$ in the S2 scenario (not shown). It can also be detected the increase of the pollutant plume with higher concentrations and its spreading towards the centre and the southern part of the country. At this time Coimbra district registers a decrease on the ozone levels (S2-C1) (-10 μg $m^{-3}$) that may be related with the higher amounts of forest fire emissions released in this region. It is also possible to see a clear increase on the $O_3$ plume concentrations northern and southern of Coimbra. The increase on the $O_3$ levels reaches approximately 27 μg $m^{-3}$ and 28 μg $m^{-3}$ for the S1 and S2 scenario, respectively.

By the end of the afternoon, at 18 UTC, the ozone plume differences (scenario S2-C1) with higher concentrations diminishes its extension and a decrease pattern can be clearly identified in the centre of Portugal (districts of Viseu, Coimbra, and Castelo Branco). The ozone precursor’s emissions due to forest fire activity are consuming the ozone that was previously produced. This decrease can reach up to –30 μg $m^{-3}$. It can also be observed the decrease of the ozone concentrations over a larger extension in the surroundings of the main Portuguese cities like Porto and Lisbon. At 21 UTC there is an $O_3$ consumption region in the southern inner part of the domain due to the reduction of the photochemical activity and to the pollutants plume spreading towards the southeastern part of the domain (Appendix F).

The monthly and the hourly analysis of the average ozone patterns over Portugal allow verifying that climate change alone may significantly impact the pollutant levels in the atmosphere especially in July and August. For instance, the projected increases on temperature in summer may deeply influence the kinetic rates of the atmospheric chemical cycles. The projected impacts of climate change on the BL height, wind speed and relative humidity may also influence the obtained ozone concentration patterns.

The interaction between the emitted pollutants and the overall chemical reactions in the atmosphere under a changing climate may lead to increases and decreases of ozone values depending on the region. The hourly average of the ozone daily profile gives important information regarding the pollutant patterns distribution in the vicinity of the fires and distant from their main locations. It is clearly that there is a decrease of the ozone concentrations just close to the forest fires and an increase in the surrounding areas. The diurnal evolution of the obtained ozone differences is also closely connected to the forest fire emissions hourly profiles considered in the numerical modelling that allocates the highest percentage of the released emissions from noon to 18 UTC (Table 6.4, pp 124). After 18 UTC the forest fire pollutants emitted to the atmosphere are leading to the $O_3$ consumption.

In order to better assess the distribution of the $O_3$ concentrations an analysis is performed for four locations over Portugal that are representative of rural background conditions. Figure 6.12 presents the hourly ozone concentrations between May and October for the reference, and future climate conditions with and without future forest fire emissions.

Figure 6.12 shows the increase in the $90^{th}$ percentile of the hourly $O_3$ values in all analysed stations due to the impact of climate change. The $90^{th}$ percentile of the $O_3$ values remains almost the same if the future forest fire emissions are considered or not. The $10^{th}$ percentile of the $O_3$ concentrations does not reveal any change among the analysed locations. This quantity may give indication about the $O_3$ background values over a given region. The impact of climate change on the ozone background values is an important issue within air quality management.

Concerning the monthly distribution of the ozone values it is possible to see that July, August, and September present the highest changes on the $90^{th}$ percentile of the ozone concentrations due to climate change and to future forest fire emissions. These are the months with highest photochemical production and this can be enhanced under future climate conditions throught, for instance, the increase of the temperature that may change the reactions rates and the photolysis rates important for the $O_3$ chemistry. It is also important to note that during these months there is a clear increase on the maximum values. The simulation that considers climate change and future forest fire emissions shows a decrease on the minimum ozone concentrations in May, August, and September. On the other hand, June, July, and October exhibit an increase on the $10^{th}$ percentile of the ozone levels.

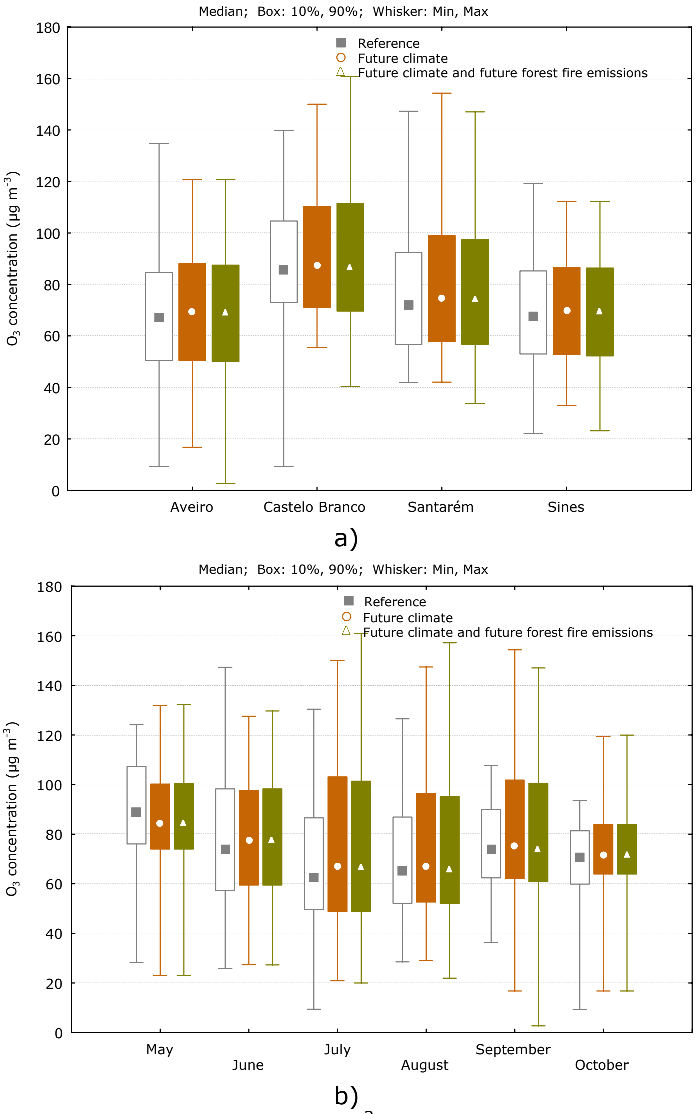



Figure 6.12 – Hourly ozone concentrations (µg $m^{-3}$) for reference (grey), future climate (orange) and future climate with future forest fire emissions (green) between May 1st and October 30th by a) location and by b) month.

Regarding particulate matter, Figure 6.13 shows the monthly mean of surface $PM_{10}$ changes from May to October between the 2100 climate and the 1990 climate over Europe estimated with the MM5/CHIMERE modelling system. The obtained changes in $PM_{10}$ surface levels are only due to climate change impact.

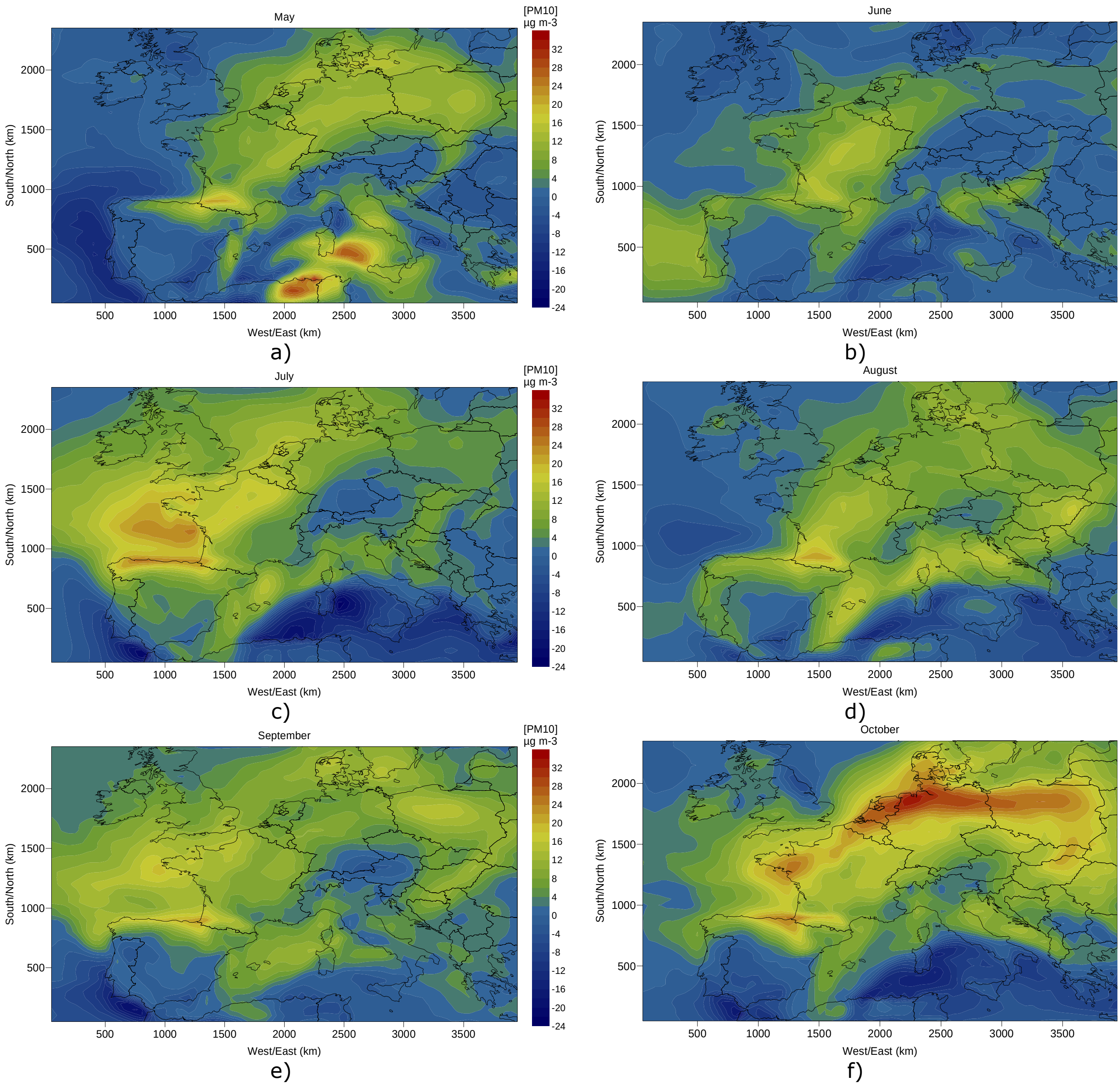



Figure 6.13 - Monthly mean surface $PM_{10}$ changes simulated over Europe with MM5/CHIMERE modelling system between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

As can be detected in Figure 6.13 the $PM_{10}$ monthly average values over Europe may register increases and decreases depending on the region. Typically the registered increases are located over the continental regions and the decreases over water. This may be related to the BL height and to the relative humidity average differences between reference and future climate (Appendix E). Wind speed differences may also contribute to the $PM_{10}$ change patterns. For instance, in October the MM5 outputs at the European scale point to an average decrease of the BL height and the wind speed, which may explain the increase on the $PM_{10}$ concentrations over Central Europe. The $PM_{10}$ concentrations can increase almost 32 µg $m^{-3}$. In July, $PM_{10}$ increases are also expected over northern Iberian Peninsula and the Gulf of Biscay and that may also be related to a decrease on the average BL height and on the average wind speed.

Wind speed, mixing heigh, and relative humidity are the meteorological variables believed to mostly influence PM concentrations. Stagnant conditions are thought to correlate with high PM concentrations, as they allow particulates to accumulate near the earth's surface. Although high wind speeds can increase ventilation, they are normally correlated with high PM concentrations because they allow the resuspension of particles from the ground, as well as long-range transport of particulates between regions. High PM concentrations are normally associated with dry conditions due to increased potential to resuspension of dust, soil, and other particles. In the southwest United States the moisture levels, namely the relative humidity, is the strongest predictor of PM concentrations [Wise and Comrie, 2005].

Particulate matter is an important pollutant emitted from forest fires that can lead to severe air pollution episodes and visibility impairment [Valente *et al.*, 2007]. In section §6.3.1 significant statistical correlations have been established between forest fires and $PM_{10}$ levels in the atmosphere which justifies the assessment of climate change and future forest fire emissions impacts on this pollutant.

Figure 6.14 depicts the monthly average of the $PM_{10}$ changes for July, August, and September considering only climate change and climate change and future forest fire emissions. The months of May, June, and October are compiled in Appendix F.

The forest fire emissions in future climate do not seem to increase the $PM_{10}$ average levels in the months of May and June (Appendix F). Only due to climate change impact the $PM_{10}$ concentrations diminish almost 36 µg $m^{-3}$ over Porto region in May. In the rest of the country the values register a maximum increase of 4 µg $m^{-3}$. In June the range of variation of the $PM_{10}$ concentrations goes from -10 µg $m^{-3}$ over Porto region to +10 µg $m^{-3}$ along the coastal regions.

In July it is possible to see the different plume patterns between simulations considering or not the future forest fire emissions. The $PM_{10}$ levels increase 20 µg $m^{-3}$ over Porto region due to climate change and future forest fire emissions. Only due to climate change the $PM_{10}$ levels in July may raise up to 18 µg $m^{-3}$. The influence of future forest fire emissions is visible in the $PM_{10}$ plume extension presenting higher concentrations over Porto, Coimbra, and Viseu districts. It is clearly visible that the registered increases are located in the north and centre part of Portugal. The $PM_{10}$ values diminish over the Atlantic Ocean and over the coast in Sines region.

In August the $PM_{10}$ plume shows its highest concentrations again over the centre of Portugal and in Bragança district for the simulation considering climate change and future forest fire emissions. The maximum increase in $PM_{10}$ values is 15 μg $m^{-3}$ considering only climate change and 16 μg $m^{-3}$ under climate change and future forest fire emissions. The $PM_{10}$ dispersion plume clearly shows the influence of the forest fires emissions on the atmospheric concentrations of this pollutant.

September and October register the highest increases on the $PM_{10}$ values reaching 30 μg $m^{-3}$ and 26 μg $m^{-3}$, respectively, just due to climate change. The maximum increases are always observed over Porto region. In September, the increase on the $PM_{10}$ values due to climate change and future forest fire emissions are visible in the pollutants dispersion plume with higher values over Coimbra, Viseu, and Castelo Branco districts with a maximum increase of 32 μg $m^{-3}$. In October (Appendix F) there is a clear increase in the $PM_{10}$ concentration plume values when forest fires and climate change are analysed together.

In summary, the monthly $PM_{10}$ average values revealed that climate change may deeply impact its levels in the atmosphere. The Porto region is the most affected one in terms of $PM_{10}$ increases. Nowadays Porto region faces specific air quality problems closely related to the high levels of $PM_{10}$ that are registered at the monitoring network [Monteiro, 2007; Ferreira, 2007].

The months of July, August, and September present a clear increase in the $PM_{10}$ levels due to climate change and the inclusion of future forest fire emissions reaching concentration increases of 32 μg $m^{-3}$. Climate change alone may increase the $PM_{10}$ average levels in 30 μg $m^{-3}$. At some extent this should be related to the different dispersion characteristics that may prevail in future climate namely related to BL height, relative humidity and wind speed.

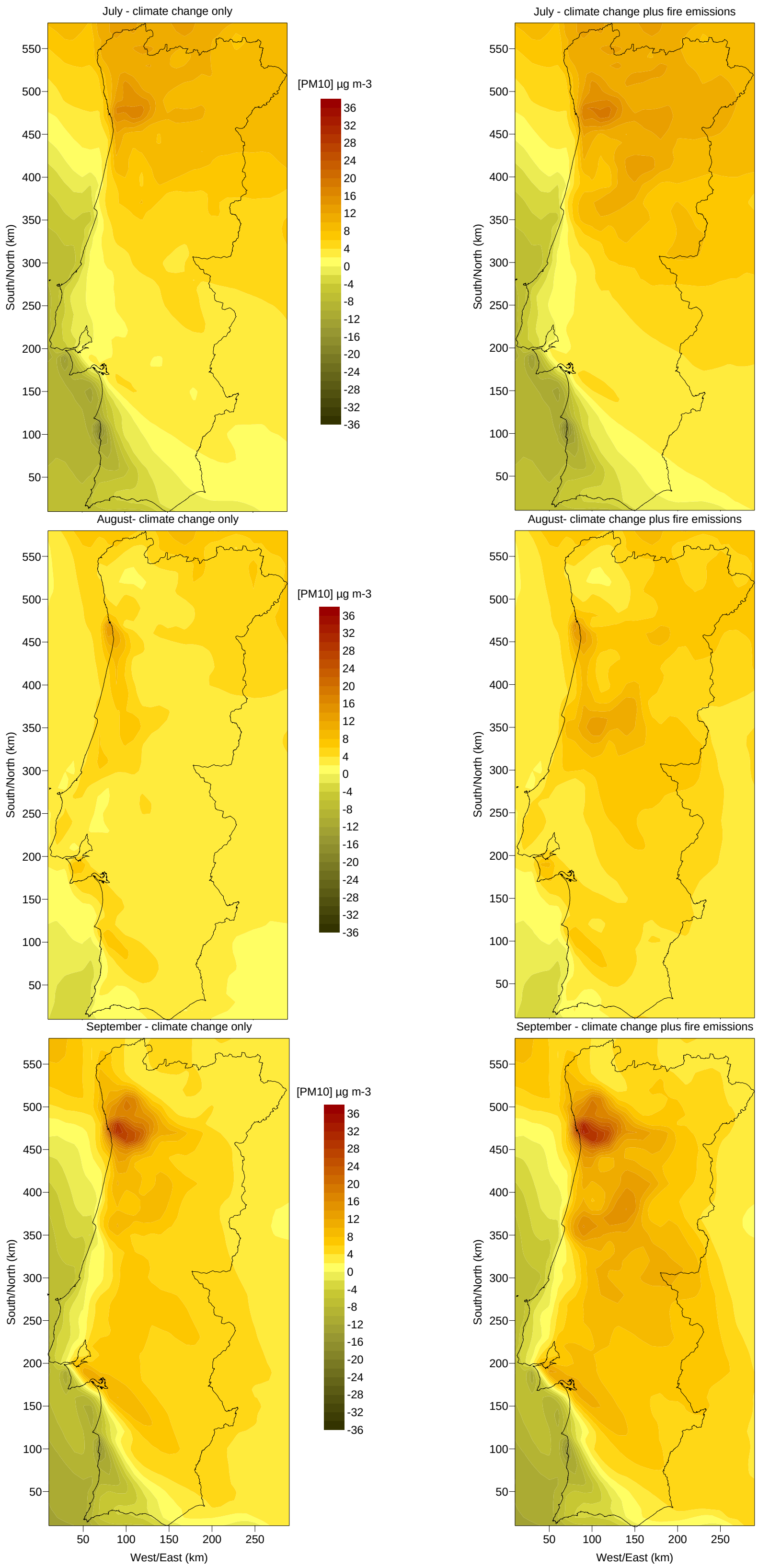



Figure 6.14 - Monthly average $PM_{10}$ concentrations over Portugal considering climate change only (S1 – C1) and climate change and future fire emissions (S2 – C1) for July, August and September.

## 6.4. Summary and conclusions

This study investigated the impact of climate change and future forest fire emissions on air quality over Portugal under the IPCC SRES A2 scenario.

Considering that forest fires release large amounts of pollutants to the atmosphere, firstly a statistical analysis was performed in order to assess the relationship between forest fire activity and $PM_{10}$ and $NO_2$ levels in the air. The 1995-2005 period was analysed, at district level, and significant correlation coefficients were obtained. $PM_{10}$ daily average and the daily number of fires present significant correlation coefficients especially in August and in Porto district reaching almost 0.90. The $NO_2$ maximum concentrations also reach the highest correlations for August with the area burned in Vila Real district (0.68). This analysis pointed out to significant correlation between forest fire activity in Portugal and the concentration of air pollutants in the atmosphere, which is highest for August when the fire activity attains its maximum.

The projected increases of area burned presented in Chapter 5 can deeply impact future forest fire emissions. Estimates of $CO_2$, CO, $CH_4$, NMHC, $PM_{2.5}$, $PM_{10}$ and $NO_x$ emissions point to substantial increases in future climate due to area burned increases. The annual $CO_2$ equivalent emissions due to forest fire activity account for 1.27 Mton for the 1980-1990 period and 7.44 Mton in a 2 x $CO_2$ scenario.

Numerical simulations performed with the MM5/CHIMERE modelling system over Europe and over Portugal indicated considerable changes of $O_3$ and $PM_{10}$ levels in the atmosphere under future climatic scenario.

For 2100 and under the IPCC SRES A2 scenario, the $O_3$ monthly mean levels in the atmosphere may increase almost 47.3 $\mu g\ m^{-3}$ over Europe in July. This estimate only considers the impact of climate change because the anthropogenic emissions were kept constant. Over Portugal, in July, this increase may reach 20 $\mu g\ m^{-3}$. If the influence of future forest fire activity is considered, the $O_3$ concentrations may rise 23 $\mu g\ m^{-3}$ by 2100 but a decrease of almost 5.6 $\mu g\ m^{-3}$ is detected over the main forest fire locations.

Based on the analysis of the hourly $O_3$ concentrations beween May 1$^{st}$ and October 30$^{th}$ for rural background sites in Portugal increases in the maximum and the minimum values can be expected by the end of the XXI century. This trend gives important information regarding the obligation to follow the national and European air quality standards. The changes in the 10$^{th}$ percentile of the ozone values also gives indication on the possible increase of the background concentrations of this pollutant.

These detected changes represent fundamental information regarding the implementation of measures to decrease the ozone precursor's emissions in order to reduce the ozone peak values but also to take into account its background conditions. A time-series filtering method performed in Carvalho [2006] already revealed that the ozone concentrations long term trend is being increasing over Portugal since 1999. The implications of these impacts in the fulfilment of the national and European air quality standards constitute a matter of great concern namely for policy makers, environment agencies and general public.

The months of July, August and September clearly exhibit the influence of the forest fire emissions on the $PM_{10}$ concentration plume over Portugal. The influence of future forest fire emissions is visible in the $PM_{10}$ plume extension presenting higher concentrations in the north and centre of Portugal.

Climate change deeply impacts the $PM_{10}$ levels in the atmosphere. The projected impacts may be related to changes in the climate/meteorological characteristics that influence the $PM_{10}$ chemical and physical mechanisms. Changes in the boundary layer height, relative humidity, wind speed, temperature and precipitation may deeply impact the advection, deposition, coagulation and absorption processes that lead particulate matter transformation and transport in the atmosphere.

The performed simulations revealed that there may be significant increases of $O_3$ and $PM_{10}$ levels in the atmosphere under future climatic scenario and forest fire emissions but decreases may also be registered in specific regions over Portugal. The complexity of the involved reactions and mechanisms in conjunction to climate change and future forest fire emissions driving forces lead to important differences among the different Portuguese regions. The increase on forest fire emissions release to the atmosphere does not mean necessarily that ozone levels will increase and this is clearly evident in the obtained ozone change patterns. Due to the high amount of forest fire emissions the $O_3$ levels may decrease over the fire activity locations and increase downwind of these regions. The diurnal profile of the $O_3$ changes clearly shows the production and consumption patterns that may be established under future climate and forest fire conditions.

Climate change alone may deeply impact the $O_3$ and the $PM_{10}$ levels in the atmosphere. The changes in the meteorological fields that are mostly related to the advection and transformation of these pollutants also impact its concentrations in the atmosphere. Emission changes are not the only variable to be taken into account in these studies. The changes in the boundary layer height, relative humidity, temperature, radiation, wind speed and precipitation may be responsible for significant differences in the pollutants concentration patterns that may be attained in the atmosphere.

The understanding of climate change impacts and future forest fire activity on air quality constitutes an adequate tool to better assess the inter-relation between these topics. The plans and measures to be settled in the next decade in the scope of air quality management must necessarily include climate change and changes in climate variability. The Portuguese authorities and policy-makers must design and implement mitigation plans in the scope of forest fire emissions reduction and air quality management and its potential implications in international commitments, e.g. the Kyoto Protocol, and subsequent impacts on human health and environmental resources.

# 7. Summary and general conclusions

The main aim of this study was to evaluate the impacts of the IPCC SRES A2 climatic scenario on forest fire activity and on air quality over Portugal. The work was organized in seven chapters starting with the overall introduction to the selected topics - climate change, forest fires and air quality – and their relationships.

Firstly, the regional scale weather patterns mostly related to forest fires in central Portugal and their temporal and spatial variations were established. The daily area burned in central Portugal was correlated with atmospheric fields provided by the ERA40 data for the period between 1980 and 2001. The study pointed to specific conditions that characterize the weather patterns before and after a forest fire event, revealing that up to five days in advance of a fire event, the temperature shows high values above central Portugal and the Spanish Extremadura region. The specific humidity shows a similar characteristic with low values in advance, minimum during the fire event and rapid increase after the event. The analysis between the Iberian thermal low and area burned suggested that in the pre-phase of a wildfire heated air is transported from the peninsula’s centre towards Portugal.

In Chapter 3 a statistical analysis was carried out in order to determine the surface fire weather conditions that explain the majority of the observed area burned and number of fires in Portugal between 1980 and 2004. The results pointed to highly significant relationships among the forest fires and the weather and the Canadian fire weather index system. The applied methodology succeeded in explaining from 60.9 %

to 80.4 % of the variance for area burned and from 47.9 % to 77.0 % of the variance for the number of fires. Fire weather conditions explained the majority of the area burned in Portugal and for the number of fires this is also true although to a less extent. This fact is related to other factors than meteorology that are closely connected to the occurrence of forest fires. Human activities have a major impact on the forest fire starts in Portugal competing with the natural weather conditions that prevail during summer months.

It is important to note that it is expected that the weather and the fire weather risk variables be related to forest fire activity, although the extent of this relationship is particular to each fire prone region. The forestry management, the prevention campaigns and the fire suppression efforts are important variables that have major influence on the fire statistics of a region. The way the natural conditions like weather, land-use and topography interact with forestry management, fire suppression and human activities give indication on how these different variables are more or less important in the characterization of the fire statistics. As described, in Portugal forest fires are closely related to the weather conditions. The forestry management and the prevention campaigns and the fire suppression activities are still insufficient to face weather conditions and human behaviour. An interesting exercise would be to include variables related to the fire suppression activities and forestry management practices in the regression models in order to better assess the importance of these tools as fire activity control variables and to project the financial effort and best practices to face a changing climate in a near future.

The characterization of the regional weather patterns and the surface weather conditions that explain the majority of the forest fires in Portugal constitutes a powerfull assessment tool for all the studies that analyse the impacts of future climate change on forest fire activity. The achieved results represent an important way to diagnose forest fire activity over Portugal based on the fire weather forecast on a short term basis. Using the acquired knowledge on regional weather patterns analysis it is possible to effectively forecast the most severe fire event situations over Portugal. This information may be used as a scientific support tool for the fire management agencies helping on a more accurate organization of the fire fighting resources and activities and also to support prevention campaigns and field actions well in advance of the fire season (in a monthly to seasonal basis).

The main outcomes of Chapters 2 and 3 give relevant information regarding the importance to study the impacts of climate change on fire weather and consequently on area burned and number of fires. Hence, based on the outputs of the regional climate model HIRHAM for reference (1961-1990) and future (2071-2100) climate it was possible to assess the impacts of the IPCC SRES A2 scenario on fire weather and fire severity. The impacts assessment study discussed in Chapter 4 was carried out for two spatial resolutions over Portugal, 12 km and 25 km. The analysis indicates an increase in the average and extremes values of the FWI component in all Portuguese districts. The fire weather severity attains higher values in a future climatic scenario. The districts of the north and centre of Portugal show the highest raises in the FWI component. Almost all the Portuguese districts will face at least 100 % increase on the fire weather risk during spring. The analysis also revealed that the majority of the fire weather and fire weather risk components projections present no statistical significant differences between the 12 km and the 25 km simulations.

Class frequency and percentile estimations of the FWI system components were evaluated for both climates and for each Portuguese district. The obtained cumulative frequency functions clearly show the fire weather severity shifts to attain higher values in a future climatic scenario. The districts of the north and centre of Portugal show the highest increases in the FWI cumulative frequency distribution. This fact may be closely related to the occurrence of a higher number of extreme events under the SRES A2 scenario. The occurrence of these extreme weather conditions will dramatically influence forest fire activity over Portugal. The proposed diagnostic tools investigated in Chapters 2 and 3 may have an important role in the prevention of disastrous fire seasons due to the forecast of the extreme weather conditions and its potential implications on fire occurrences and area burned.

The impacts of future fire weather on the area burned and on the number of fires were discussed in Chapter 5. The 12 km and 25 km projections were used to forecast the future area burned and number of fires over Portugal. The results point to a substantial increase on area burned and on number of fire starts ranging from 238 % to 643 % and 111 % to 483 %, respectively, depending on the district. The monthly distribution of the area burned and the number of fires indicates that an earlier fire season starting may be expected under future climatic scenario. These findings indicate important modifications on the fire activity annual cycle over Portugal. In addition, this study revealed that the historical relationships established between the area burned and the number of fires and the weather and the FWI components for current climate conditions (Chapter 3) had to be re-evaluated in order to be applied under future climatic scenarios. The most adequate tool to currently diagnose the forest fire activity in Portugal could not be applied based on the same assumptions in a changing climate. This may constitute an important outcome regarding the limitations of today's developed statistic analysis and its application under future climatic scenarios.

The implication of the projected area burned on future forest fire emissions and its impacts on air quality was the main objective of Chapter 6. The MM5/CHIMERE modelling system was applied for reference (1990) and future climate (2100) from May 1$^{st}$ to October 30$^{th}$. The numerical simulations pointed out that there may be significant increases of $O_3$ and $PM_{10}$ levels in the atmosphere under climate change conditions but decreases over specific regions may also be registered. For 2100, under the IPCC SRES A2 scenario, the $O_3$ monthly mean levels in the atmosphere may increase almost 47.3 μg m$^{-3}$ over Europe in July. This estimate only considers the influence of a changing climate. Over Portugal, in July, this increase may reach 20 μg m$^{-3}$. If the influence of future forest fire activity is considered the $O_3$ concentrations may raise 23 μg m$^{-3}$ by 2100 but a decrease of almost 5.6 μg m$^{-3}$ is detected over the main forest fire locations. In these regions the ozone precursor's emissions due to forest fires are depleting the previously produced ozone.

This analysis revealed that an increase on future forest fire emissions does not directly mean that ozone levels in the atmosphere will increase. The interplay between polluttants concentrations (like $NO_x$ and VOC), surface emissions, and meteorology leads to strong nonlinearities for the atmospheric ozone chemistry. The interaction between ozone precursor's emissions and ozone formation and depletion may be deeply impacted under future climatic scenarios. The knowledge of these relationships constitutes an important tool to correctly evaluate the role of forest fires on air quality under a changing climate.

The projected impacts of forest fire emissions on $O_3$ and $PM_{10}$ levels in the atmosphere raise the concern regarding the application of prescribed burning as a management tool. It is recognized that forest fires release high amounts of pollutants to the atmosphere that, in the short term, may lead to acute air pollution episodes with important human health injuries. An adequate prescribed burning planning should also consider the potential impacts of forest fire emissions on the air quality of a region. The obligation for the fulfilment of the European and national air quality standards is an important issue to be taken into account during these initiatives.

Meteorological conditions have the greatest impact on air quality daily variations. The impact of climate change on temperature, relative humidity, precipitation, wind speed and atmospheric dispersion conditions may deeply impact the air quality over a given region. The strong linkage between weather conditions and pollutant levels can obscure the effects of changing emissions levels over time. To correctly assess the effectiveness of air quality control regulations and improve air quality management efforts the meteorological/climate signal must be identified in order to better examine emissions-influenced trends and the climate change role. Changes in meteorology must be considered in any future management plans. Old assumptions may no longer be valid.

The achieved results point to dramatic consequences of climate change on future forest fire activity and on air quality over Portugal. Future developments should consider other variables that could better represent the relationship between climate change, forestry dynamics, land-use change and future human activities. The use of dynamic vegetation models and/or landscape models could better represent the interaction between weather, vegetation changes, forest fires and human activities. The application of today's developed statistical models implies that the relationships between forest fires and weather would remain the same under future climatic scenario and this may not correspond to the truth. A dynamic analysis of these interactions could lead to a better representation of the weather, fire and climate relationships.

The human influence on forest fire activity is another variable that should be addressed. Due to lack of information it was not possible to effectively assess the influence of human activities and human behaviour on forest fire numbers. This variable may change dramatically in future and thus influencing the forest fire statistics and their related impacts.

The application of more than one climatic scenario gives the opportunity to better characterize the range of possible changes that can be detected in future. An ensemble of the several possible scenarios for future climate may give important information regarding uncertainty analysis and promote a better characterization of the future forest fire activity and air quality over Portugal. The use of an ensemble approach will be particularly important to provide uncertainty information and bracket the response. This would represent an important added value to the already projected changes. The analysis of the impacts of climate change and designed pollutant emissions reduction policies would constitute an important step forward to effectively assess the impact of the implemented measures on the air quality of the next 20 to 30 years.

This work represents an important attempt to relate climate change, fores fires and air quality over Portugal. The achieved results and main outcomes constitute an adequate scientific tool to support the implementation of measures and plans in the forest fire management and in the air quality fields.

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# Appendices

# Appendix a

## Appendix A – Correlation analysis based on daily, monthly and seasonal data

Table A.1 to Table A.5 present the daily, monthly and seasonal (May 1st to October 31st) correlation analysis between area burned and number of fires and the weather and the FWI components

Table A.1 - Pearson correlation coefficients (r), for the natural logarithm of area burned, obtained on a daily basis.

| District | Pearson correlation coefficient (r) | | | | N | p |
|---|---|---|---|---|---|---|
| | TX | FWI | DSR | BUI | | |
| Bragança | 0.54 | | | 0.57 | 9132 | <0.0001 |
| Vila Real | 0.59 | 0.72 | | | 9132 | <0.0001 |
| Porto | 0.58 | | | 0.69 | 9132 | <0.0001 |
| Viseu | 0.63 | 0.73 | | | 4232 | <0.0001 |
| Coimbra | 0.53 | 0.64 | | | 9132 | <0.0001 |
| Castelo Branco | 0.59 | 0.68 | | | 7185 | <0.0001 |
| Portalegre | 0.29 | | 0.37 | | 9132 | <0.0001 |
| Santarém | 0.50 | | 0.62 | | 5479 | <0.0001 |
| Lisboa | 0.55 | 0.59 | | | 9132 | <0.0001 |
| Évora | 0.27 | | 0.37 | | 9132 | <0.0001 |
| Beja | 0.33 | | 0.39 | | 9132 | <0.0001 |
| Portalegre, Évora, Beja | 0.45 | 0.54 | | | 9132 | <0.0001 |
| Faro | 0.41 | 0.45 | | | 9132 | <0.0001 |
| All districts | 0.79 | 0.86 | | | 9132 | <0.0001 |

Table A.2 - Pearson correlation coefficients (r), for the natural logarithm of number of fires, obtained on a daily basis.

| District | Pearson correlation coefficient (r) | | | | N | p |
|---|---|---|---|---|---|---|
| | TX | FWI | DSR | BUI | | |
| Bragança | 0.55 | | 0.52 | | 9132 | <0.0001 |
| Vila Real | 0.62 | 0.72 | | | 9132 | <0.0001 |
| Porto | 0.59 | | 0.67 | | 9132 | <0.0001 |
| Viseu | 0.68 | | 0.76 | | 4232 | <0.0001 |
| Coimbra | 0.66 | 0.76 | | | 9132 | <0.0001 |
| Castelo Branco | 0.70 | 0.76 | | | 7185 | <0.0001 |
| Portalegre | 0.35 | 0.40 | | | 9132 | <0.0001 |
| Santarém | 0.58 | | | 0.68 | 5479 | <0.0001 |
| Lisboa | 0.57 | | 0.55 | | 9132 | <0.0001 |
| Évora | 0.31 | 0.39 | | | 9132 | <0.0001 |
| Beja | 0.37 | 0.41 | | | 9132 | <0.0001 |
| Portalegre, Évora, Beja | 0.49 | 0.55 | | | 9132 | <0.0001 |
| Faro | 0.52 | 0.57 | | | 9132 | <0.0001 |
| All districts | 0.77 | 0.79 | | | 9132 | <0.0001 |

Table A.3 - Pearson correlation coefficients (r), for the natural logarithm of area burned, obtained on a monthly basis.

| District | Pearson correlation coefficient (r) | | | | N | p |
|---|---|---|---|---|---|---|
| | TX | FWI | BUIP90 | FWIP90 | | |
| Bragança | 0.76 | | 0.73 | | 300 | <0.0001 |
| Vila Real | 0.74 | | | 0.79 | 300 | <0.0001 |
| Porto | 0.74 | | 0.75 | | 300 | <0.0001 |
| Viseu | 0.74 | | 0.82 | | 138 | <0.0001 |
| Coimbra | 0.79 | 0.84 | | | 300 | <0.0001 |
| Castelo Branco | 0.83 | | | 0.85 | 236 | <0.0001 |
| Portalegre | 0.65 | 0.67 | | | 300 | <0.0001 |
| Santarém | 0.82 | 0.88 | | | 180 | <0.0001 |
| Lisboa | 0.79 | | 0.77 | | 300 | <0.0001 |
| Évora | 0.61 | | | 0.65 | 300 | <0.0001 |
| Beja | 0.74 | | | 0.76 | 300 | <0.0001 |
| Portalegre, Évora, Beja | 0.76 | | | 0.78 | 300 | <0.0001 |
| Faro | 0.79 | 0.82 | | | 300 | <0.0001 |
| All districts | 0.84 | | | 0.87 | 300 | <0.0001 |

Table A.4 - Pearson correlation coefficients (r), for the natural logarithm of number of fires, obtained on a monthly basis.

| District | Pearson correlation coefficient (r) | | | | N | p |
|---|---|---|---|---|---|---|
| | TX | FWI | BUIP90 | FWIP90 | | |
| Bragança | 0.71 | | 0.64 | | 300 | <0.0001 |
| Vila Real | 0.71 | 0.73 | | | 300 | <0.0001 |
| Porto | 0.68 | | 0.66 | | 300 | <0.0001 |
| Viseu | 0.67 | | 0.82 | | 138 | <0.0001 |
| Coimbra | 0.77 | | | 0.79 | 300 | <0.0001 |
| Castelo Branco | 0.80 | 0.79 | | | 236 | <0.0001 |
| Portalegre | 0.59 | 0.59 | | | 300 | <0.0001 |
| Santarém | 0.83 | | | 0.87 | 180 | <0.0001 |
| Lisboa | 0.69 | | 0.61 | | 300 | <0.0001 |
| Évora | 0.57 | | | 0.61 | 300 | <0.0001 |
| Beja | 0.66 | | | 0.66 | 300 | <0.0001 |
| Portalegre, Évora, Beja | 0.68 | | | 0.68 | 300 | <0.0001 |
| Faro | 0.72 | 0.72 | | | 300 | <0.0001 |
| All districts | 0.76 | | | 0.77 | 300 | <0.0001 |

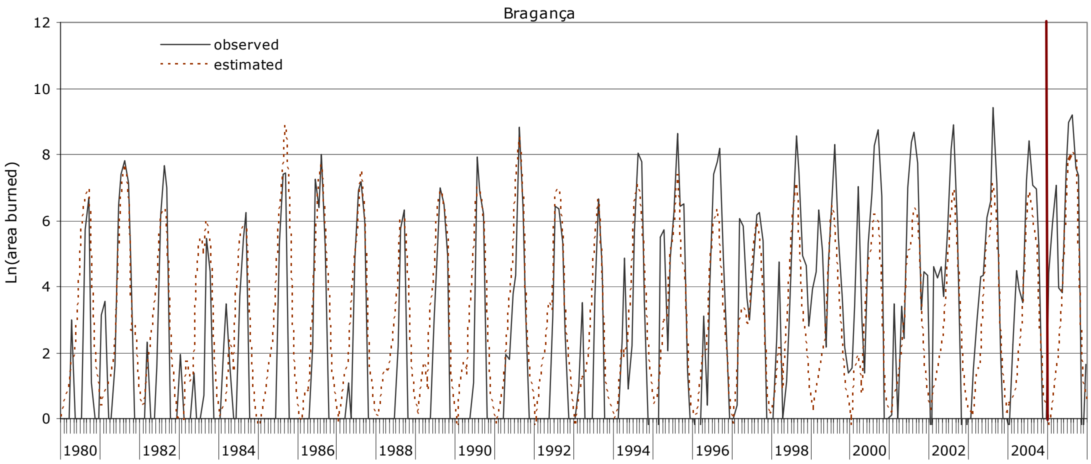
Table A.5 - Pearson correlation coefficients (r), for the natural logarithm of area burned, obtained on a seasonal (May 1st to October 31st) basis.

| District | Pearson correlation coefficient (r) | | | | | | | | | N | p |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | T | TX | TXX | TXP90 | DMC | DCX | DSRX | FFMCX | FWIP90 | | |
| Bragança | | 0.65 | | | | | | | | 25 | <0.0001 |
| Vila Real | | | | | | | | 0.49 | | 25 | <0.0001 |
| Porto | 0.49 | | | | | | | 0.67 | | 25 | <0.0001 |
| Viseu | | | | | 0.57 | | | | | 23 | <0.0001 |
| Coimbra | | | | 0.57 | | 0.59 | | | | 25 | <0.0001 |
| Castelo Branco | | 0.57 | | | | 0.69 | | | | 20 | <0.0001 |
| Portalegre | | | | | | | | | | 25 | <0.0001 |
| Santarém | | 0.81 | | | | | | | 0.82 | 15 | <0.0001 |
| Lisboa | | | | 0.56 | | | | | | 25 | <0.0001 |
| Évora | | | | | | | | | | 25 | <0.0001 |
| Beja | | | | | | | 0.49 | | | 25 | <0.0001 |
| Portalegre, Évora, Beja | | | | | | | | | | 25 | <0.0001 |
| Faro | | | 0.62 | | | | | | 0.74 | 25 | <0.0001 |
| All districts | | 0.65 | | | | | | | 0.60 | 25 | <0.0001 |

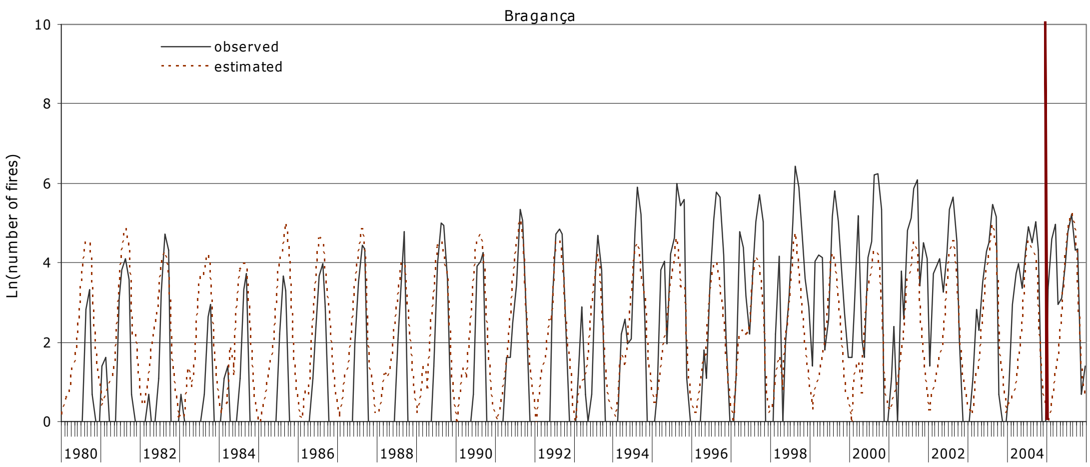
# Appendix b

## Appendix B – Observed and estimated fire activity between 1980 and 2005

Figure B.1 to Figure B.7 show the natural logarithm of the observed and estimated monthly area burned and monthly number of fires, between 1980 and 2005, by district.

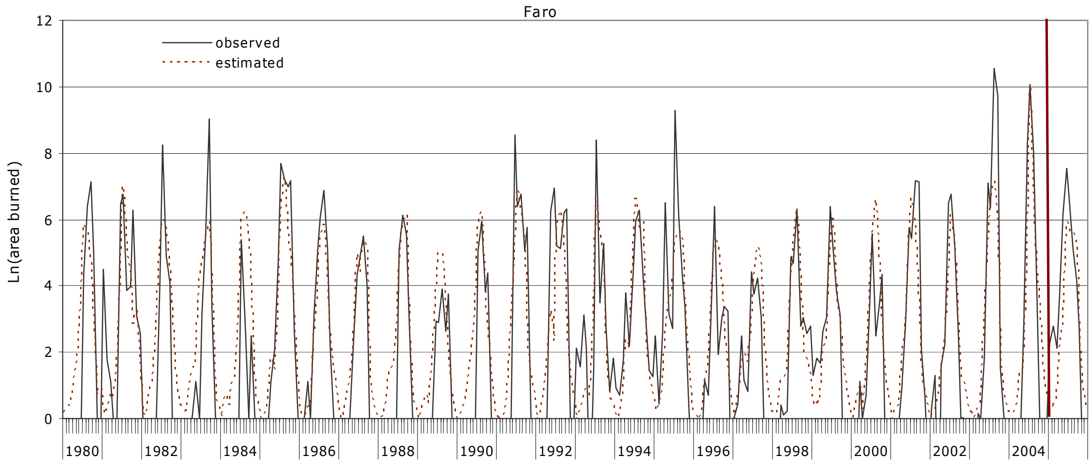



a)

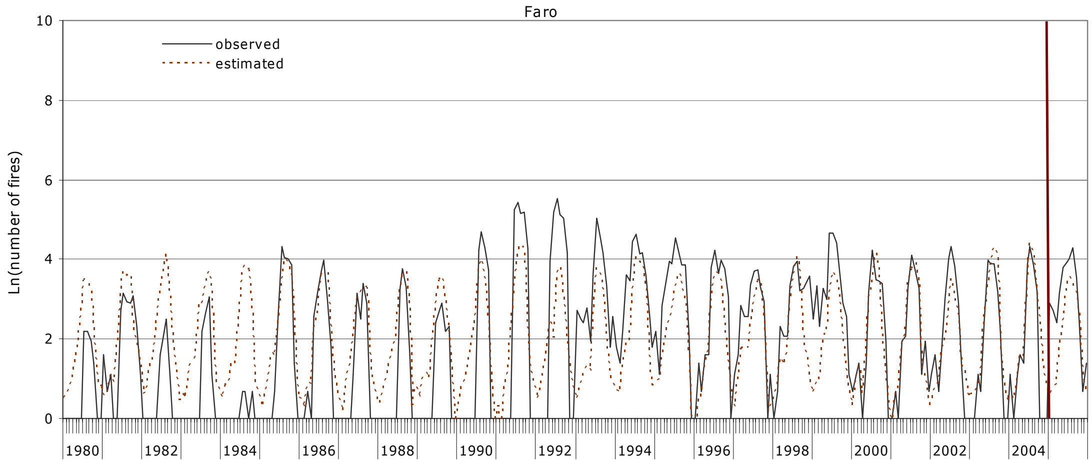



b)

Figure B.1 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Bragança district, from 1980 to 2005.

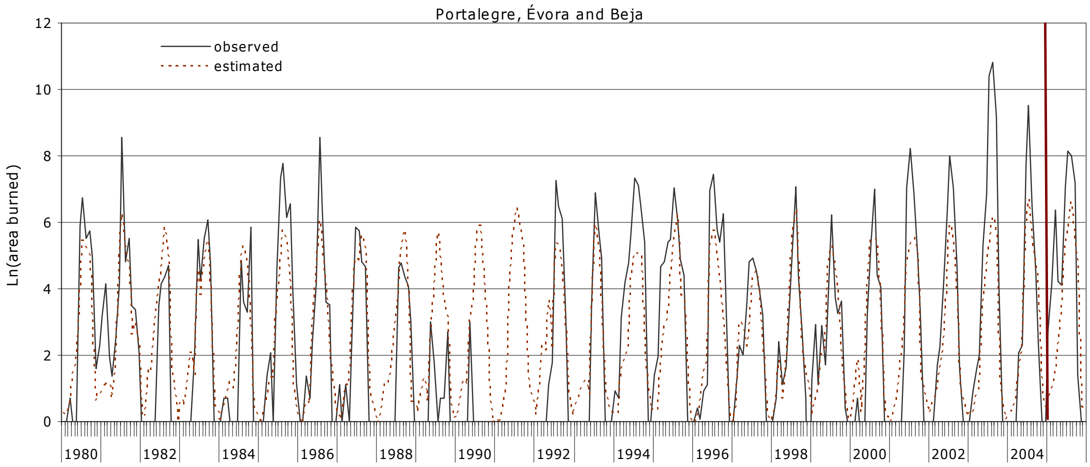



a)

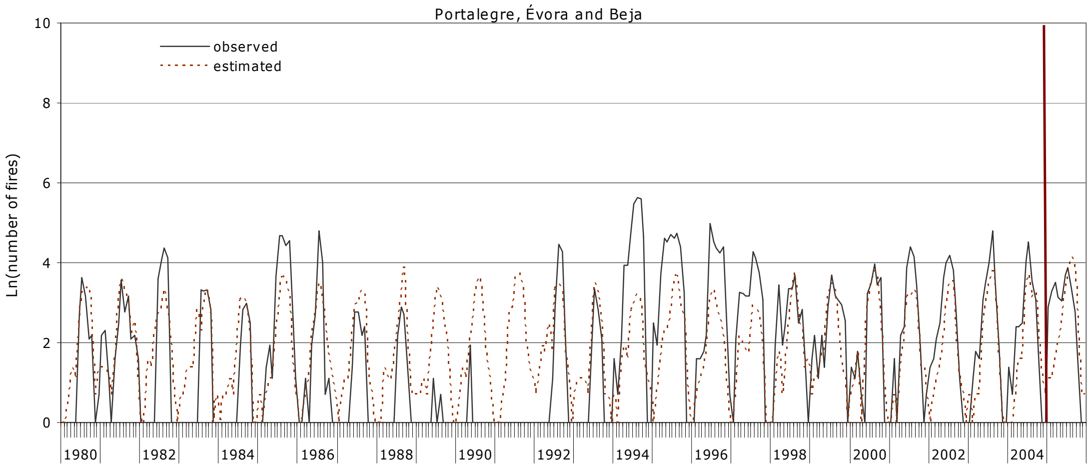



b)

Figure B.2 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Faro district, from 1980 to 2005.

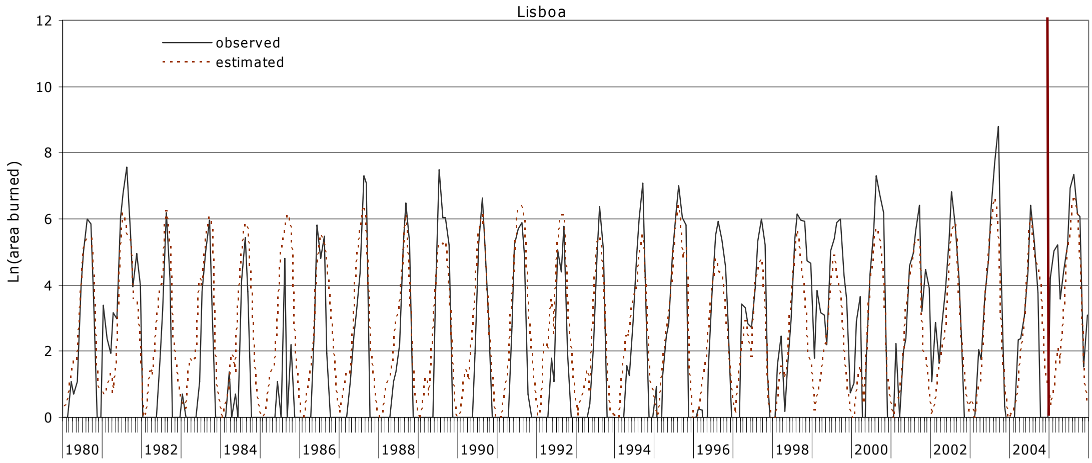



a)

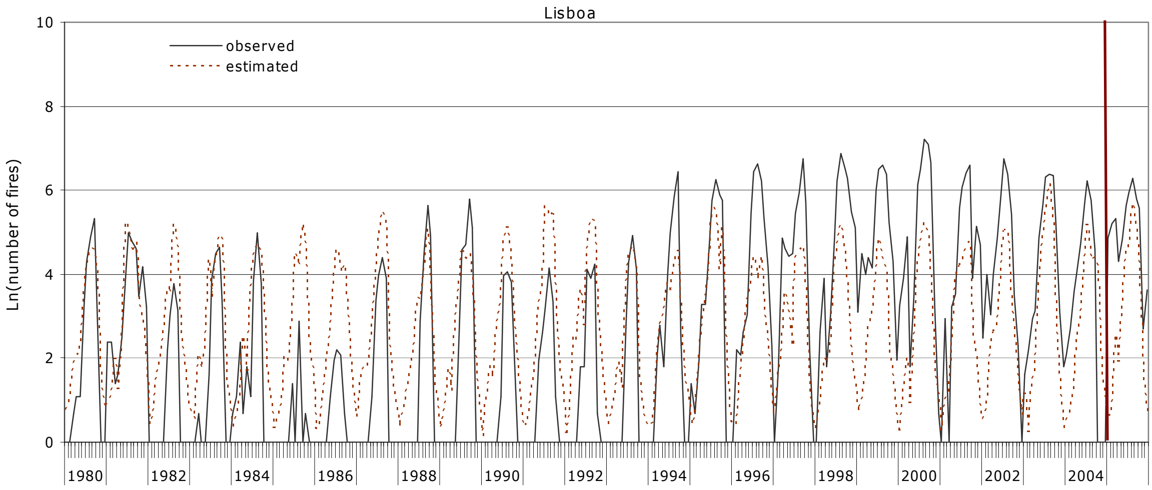



b)

Figure B.3 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Portalegre, Évora e Beja districts, from 1980 to 2005.

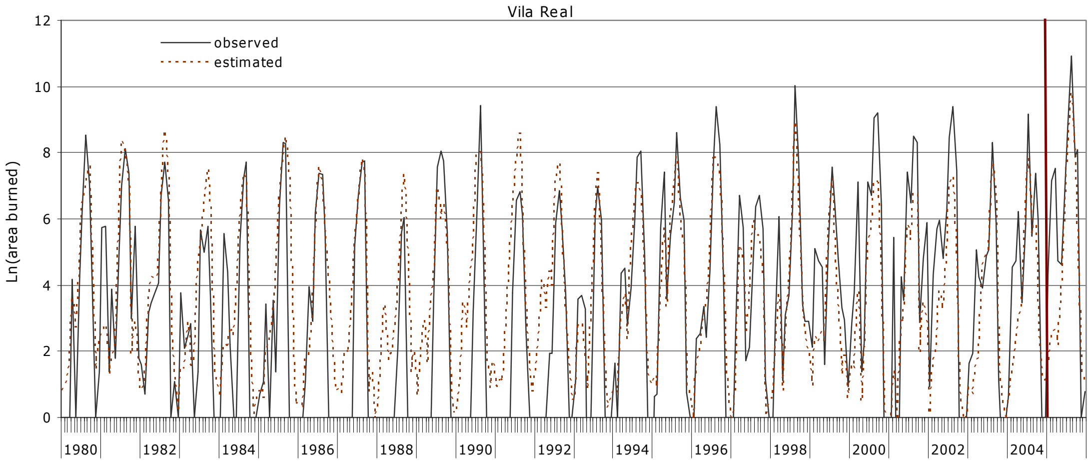



a)

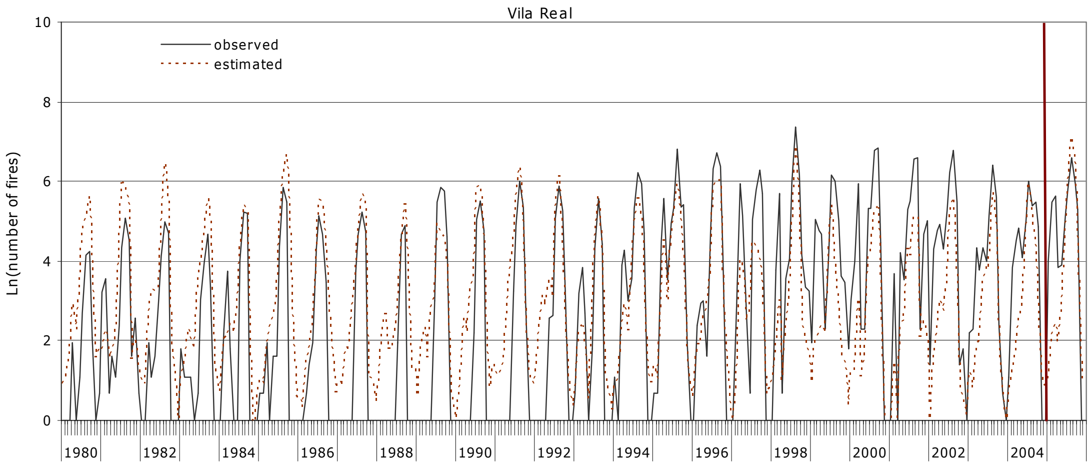



b)

Figure B.4 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Lisboa district, from 1980 to 2005.

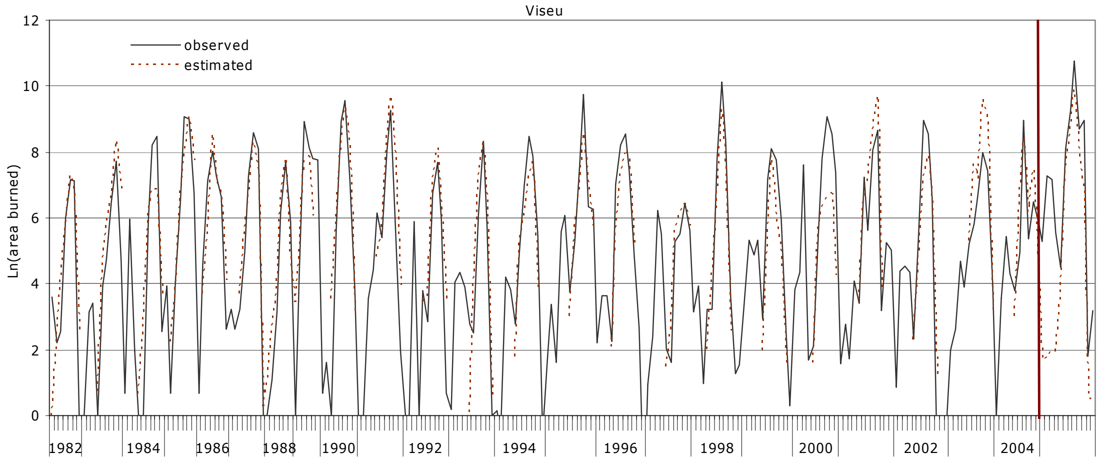



a)

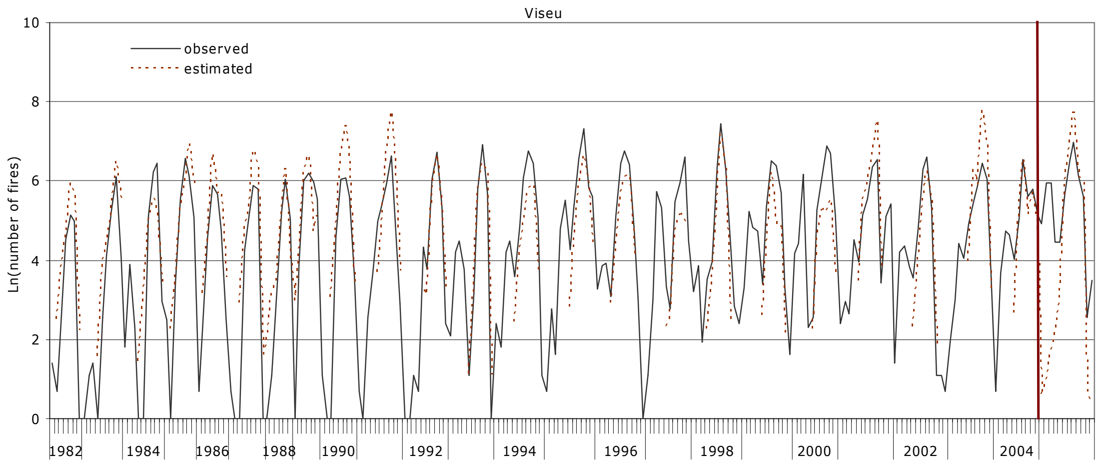



b)

Figure B.5 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Vila Real district, from 1980 to 2005.

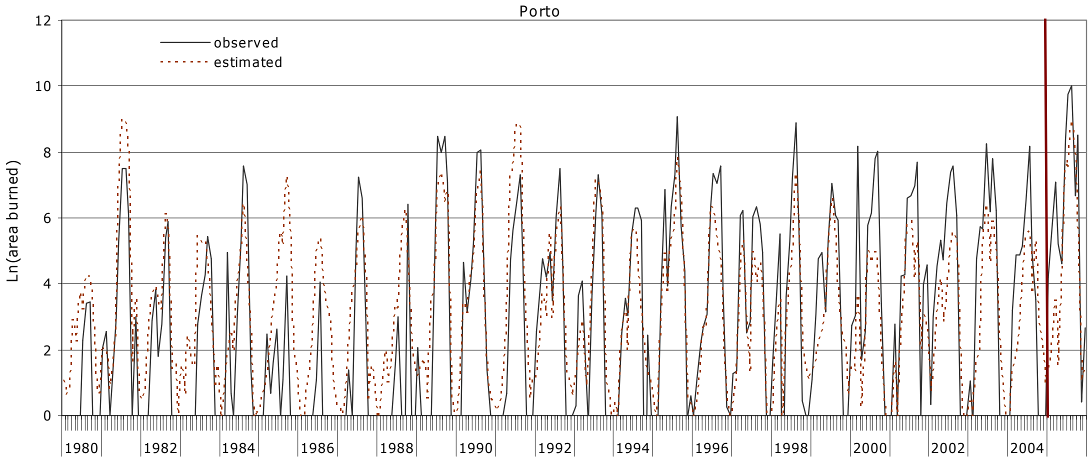



a)

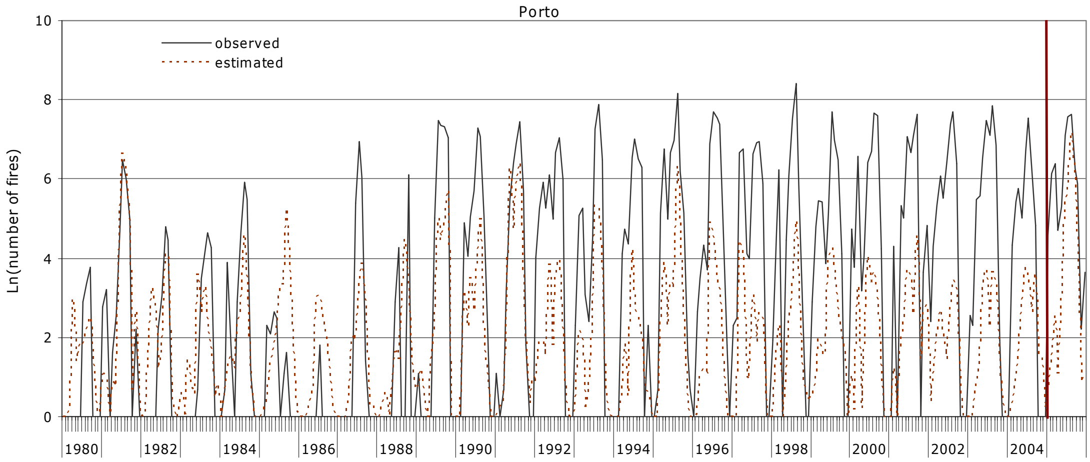



b)

Figure B.6 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Viseu district, from 1980 to 2005.




a)




b)

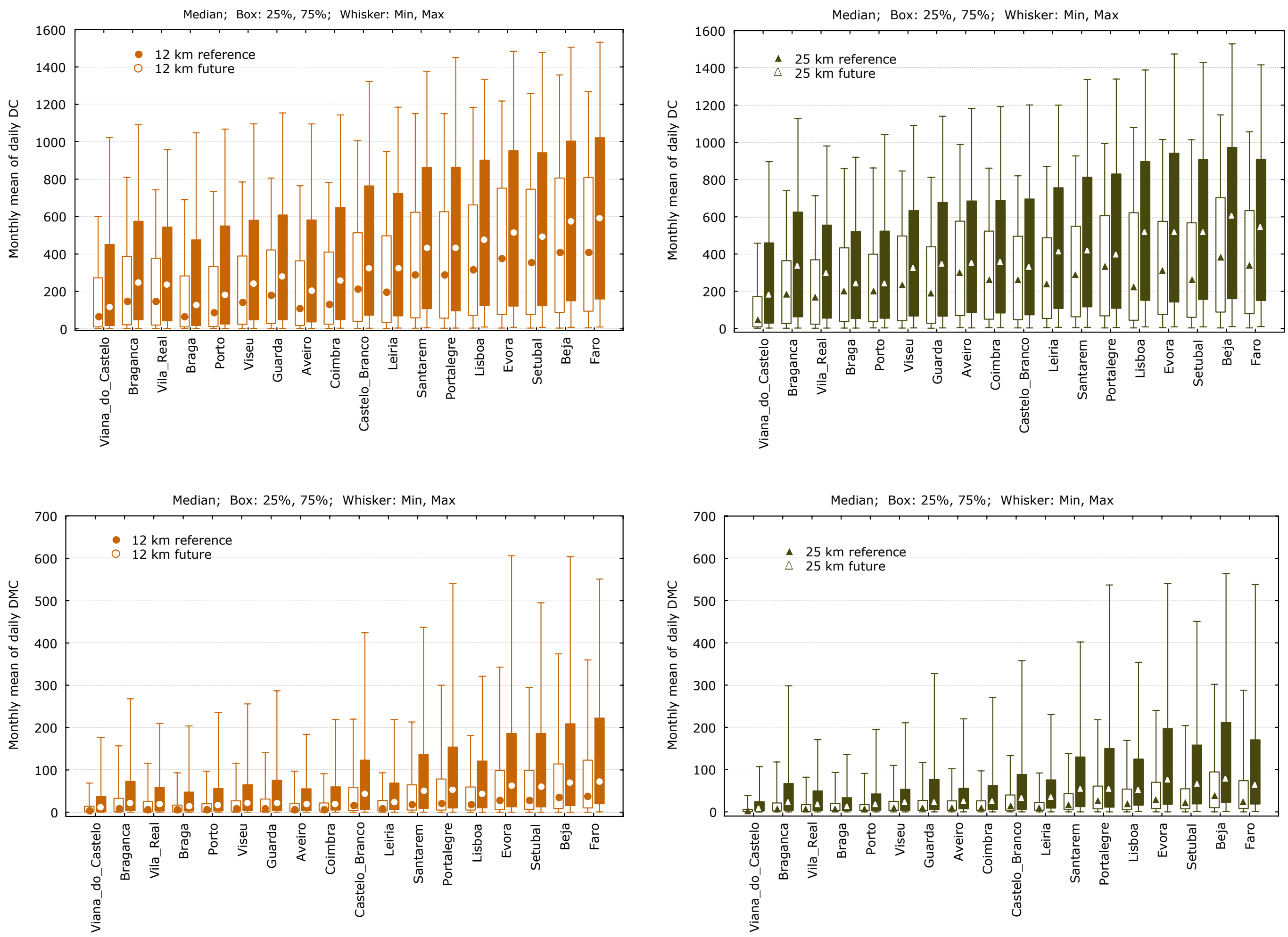
Figure B.7 – Natural logarithm of the observed and estimated a) monthly area burned and b) monthly number of fires for Porto district, from 1980 to 2005.

# Appendix C

## Appendix C – Climate change impacts on the FWI system components

Figure C.1 shows the DC, DMC, ISI and BUI, by district, for reference and future climatic scenario at 12 km and 25 km resolution.

Figure C.2 exhibits the FWI frequencies for reference and future climatic scenario.



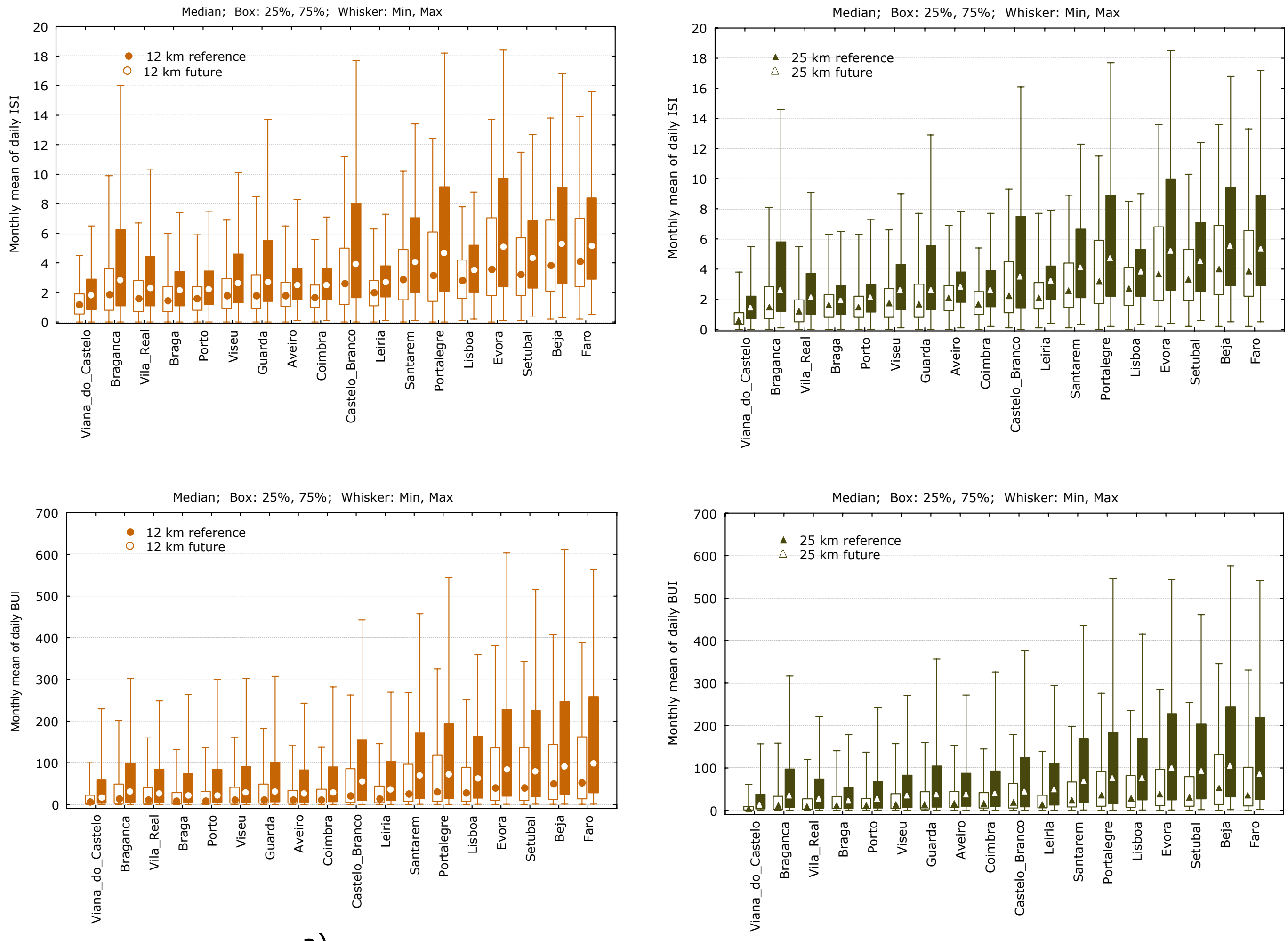
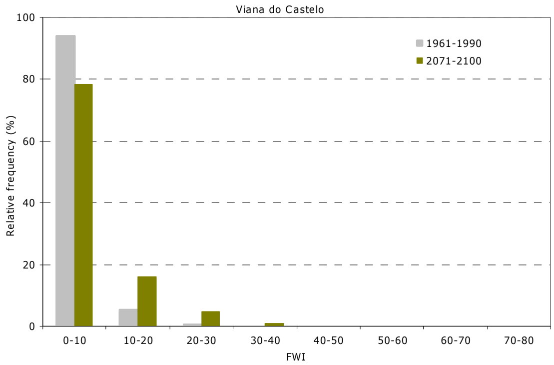
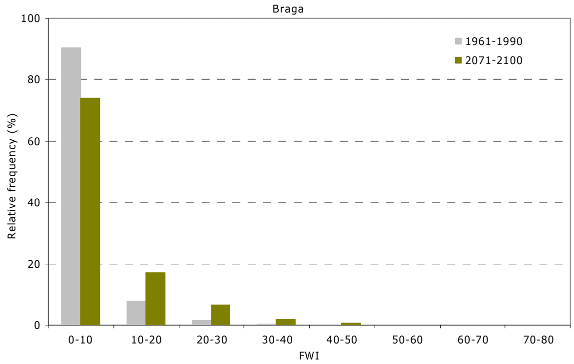
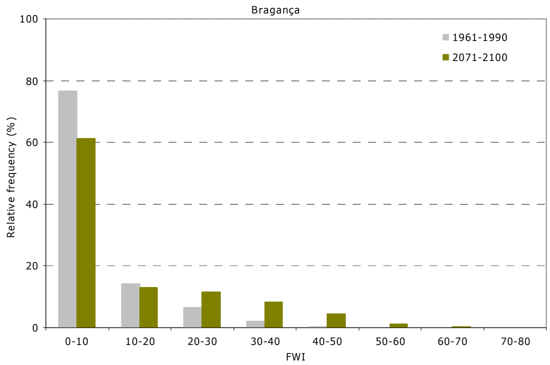
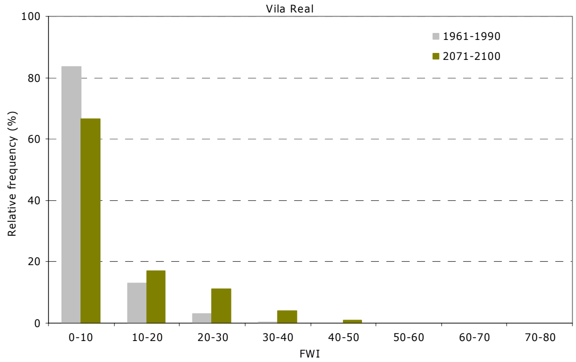


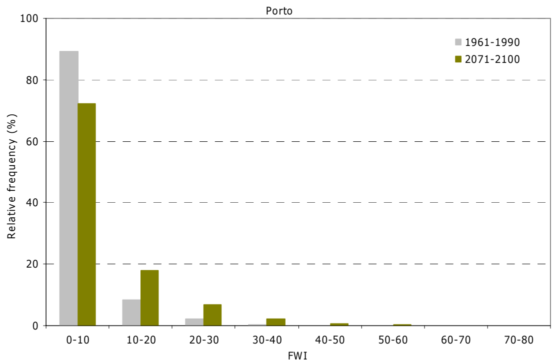

Figure C.1 - Monthly mean of daily DMC, DC, ISI and BUI components per district, for the 2071-2100 scenario (coloured boxes) and 1961-1990 scenario (open boxes) for a) HIRHAM 12 km simulation and b) HIRHAM 25 km resolution.

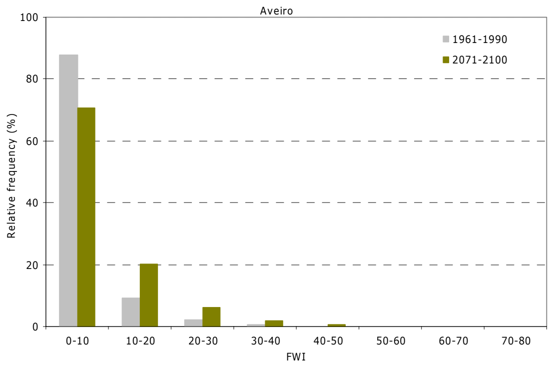

Viana do Castelo
Relative frequency (%)
FWI
1961-1990
2071-2100

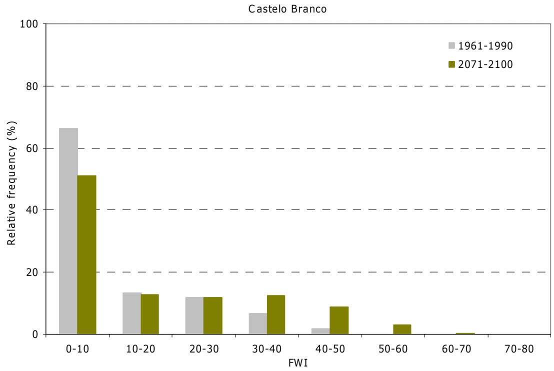

Braga
Relative frequency (%)
FWI
1961-1990
2071-2100

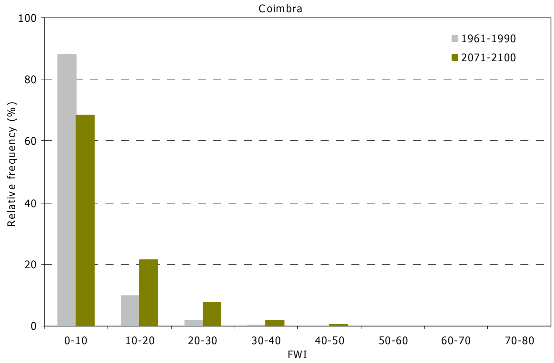

Bragança
Relative frequency (%)
FWI
1961-1990
2071-2100

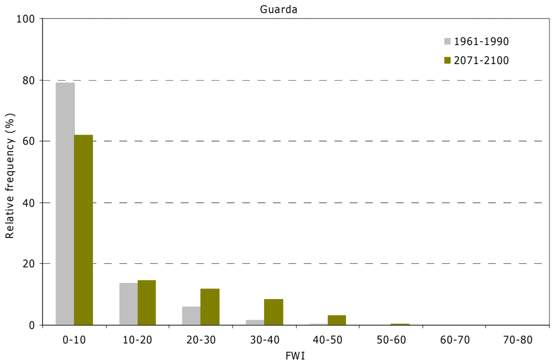

Vila Real
Relative frequency (%)
FWI
1961-1990
2071-2100

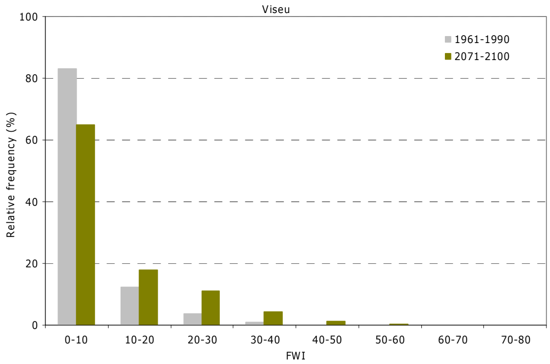

Porto
Relative frequency (%)
FWI
1961-1990
2071-2100

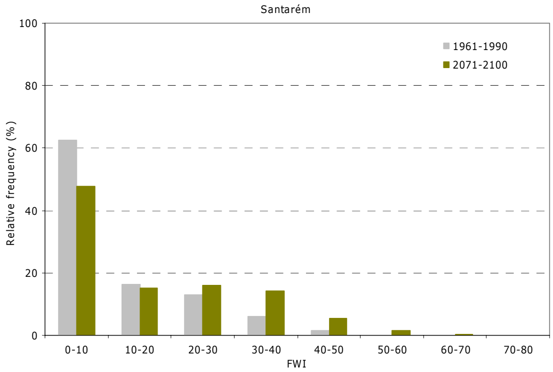

Aveiro
Relative frequency (%)
FWI
1961-1990
2071-2100

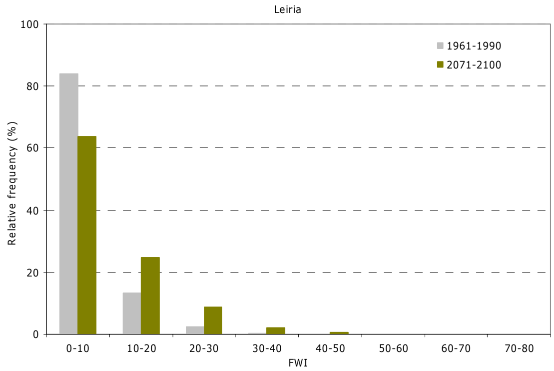

Castelo Branco
Relative frequency (%)
FWI
1961-1990
2071-2100

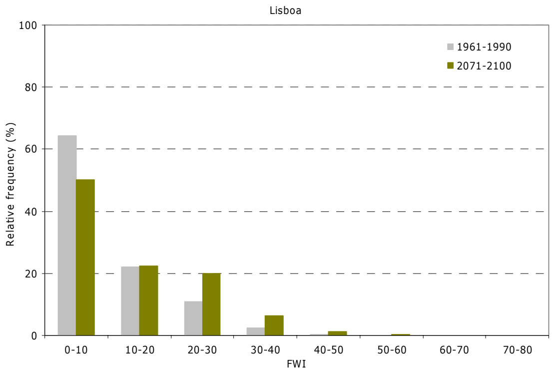

Coimbra
Relative frequency (%)
FWI
1961-1990
2071-2100

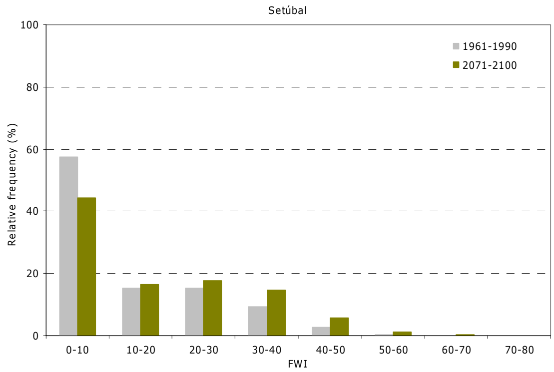

Guarda
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100

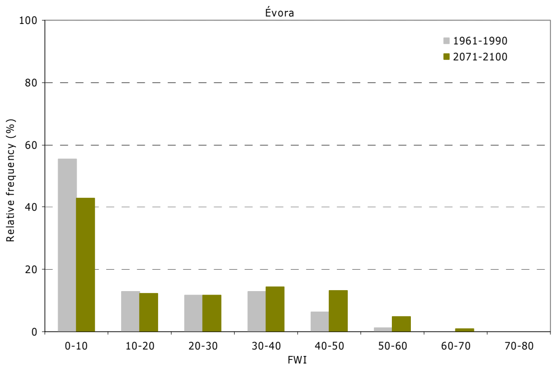

Viseu
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100

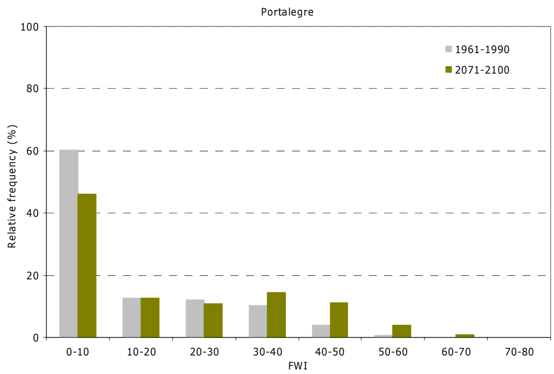

Santarém
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100


Leiria
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100


Lisboa
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100


Setúbal
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100


Évora
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100


Portalegre
Relative frequency (%)
FWI
1961-1990
2071-2100
0-10 10-20 20-30 30-40 40-50 50-60 60-70 70-80
0 20 40 60 80 100

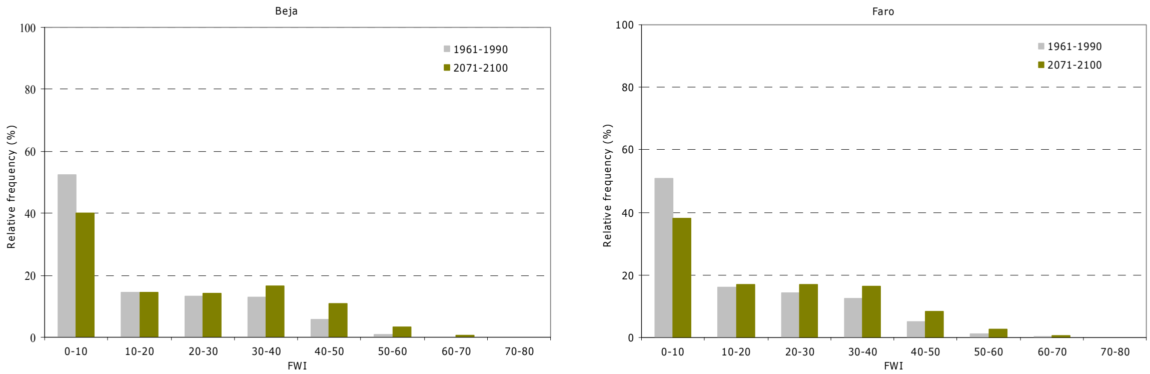
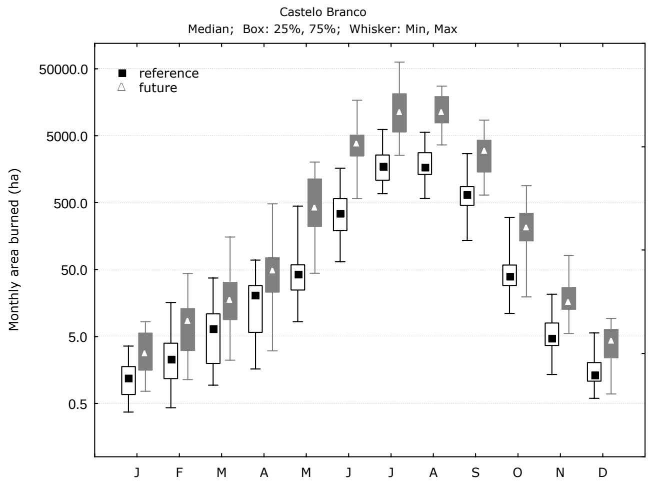


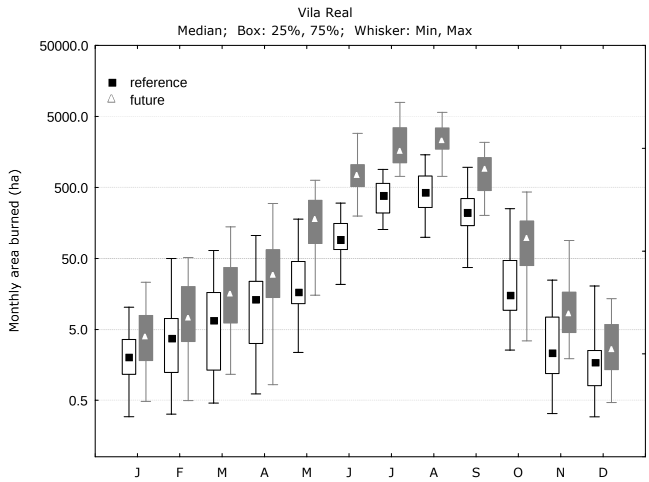

Figure C.2 - Relative frequencies of fire weather index (FWI) component, by district, for each climatic scenario (reference and 2 x $CO_2$) at 12 km resolution.

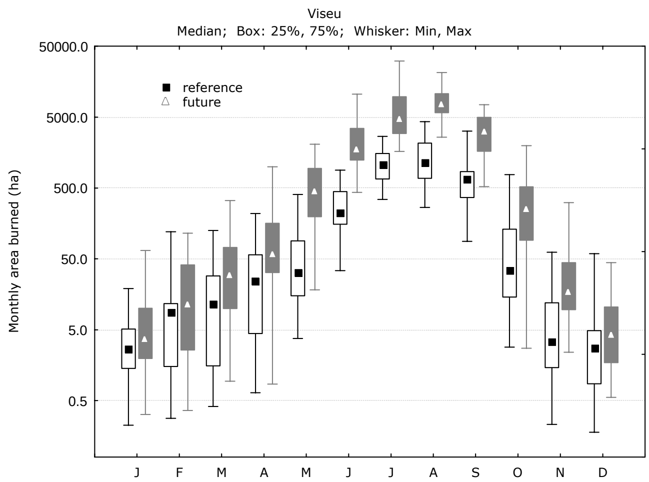
# Appendix d

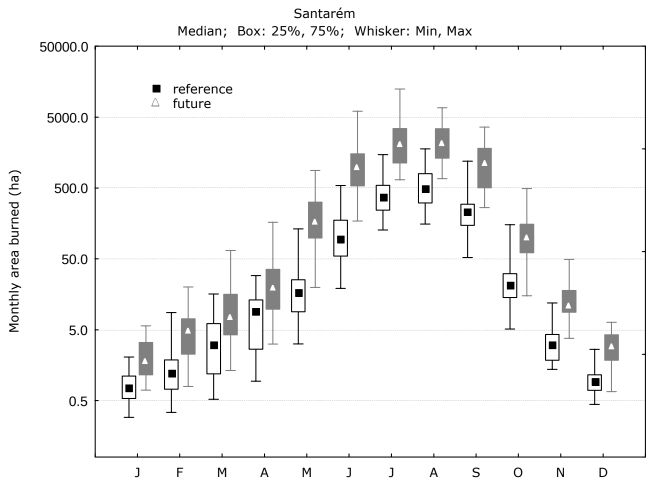
## Appendix D – Monthly fire activity for reference and future scenario

Figure D.1 and Figure D.2 present the monthly area burned and the monthly number of fires, respectively, for reference (1961-1990) and future (2071-2100) climate for the analysed Portuguese districts.



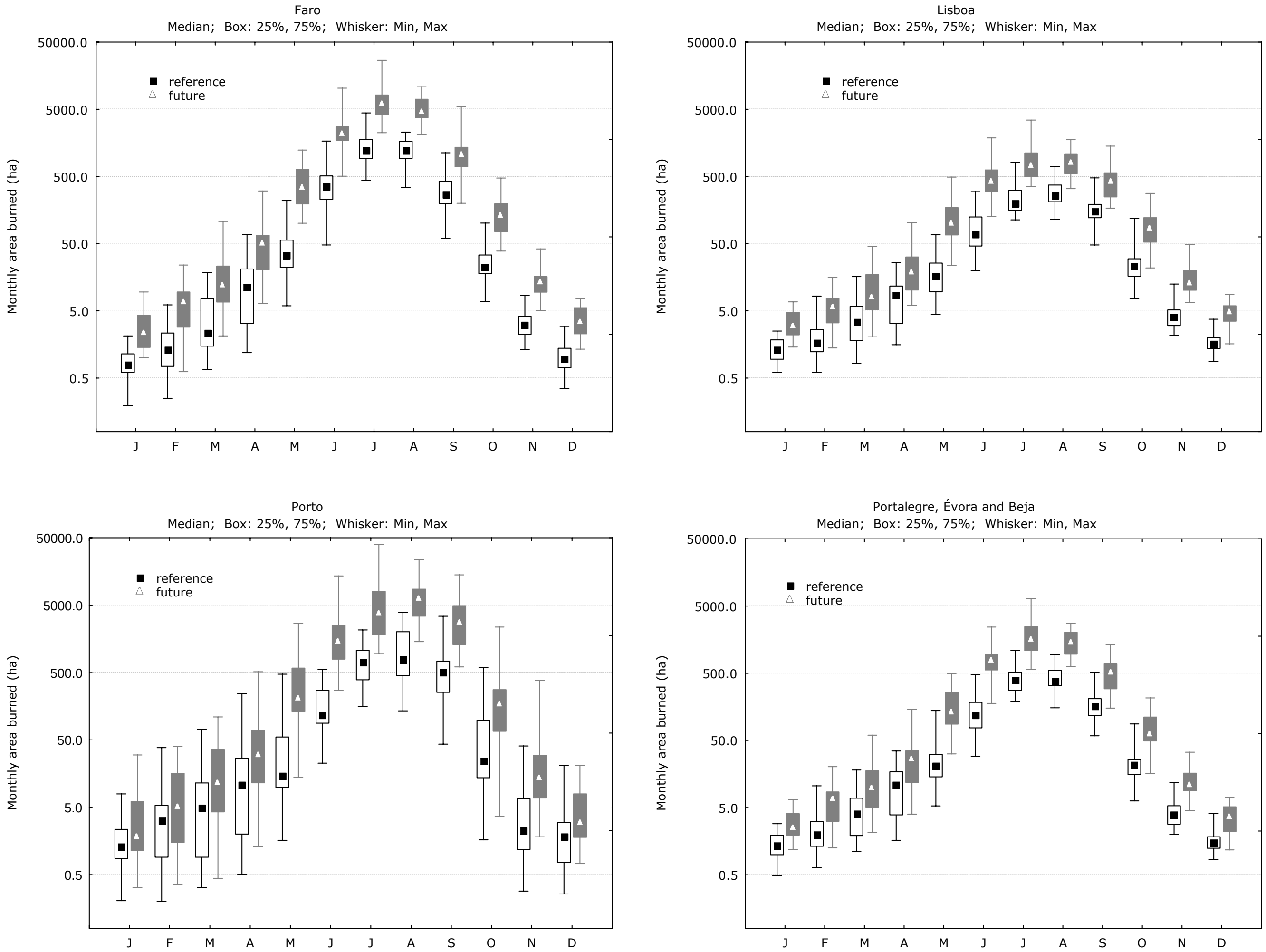
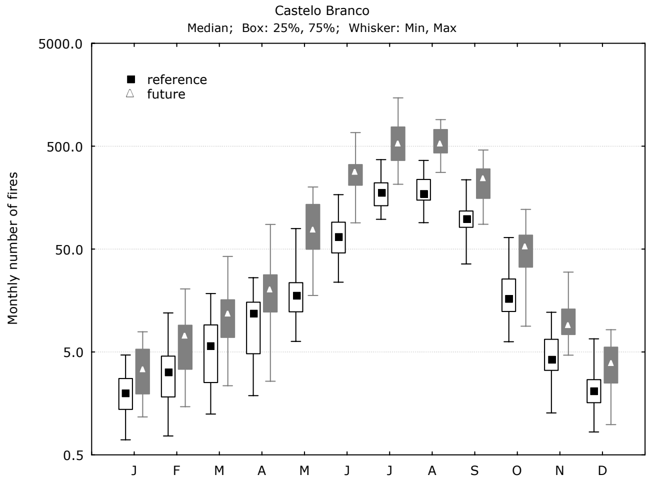
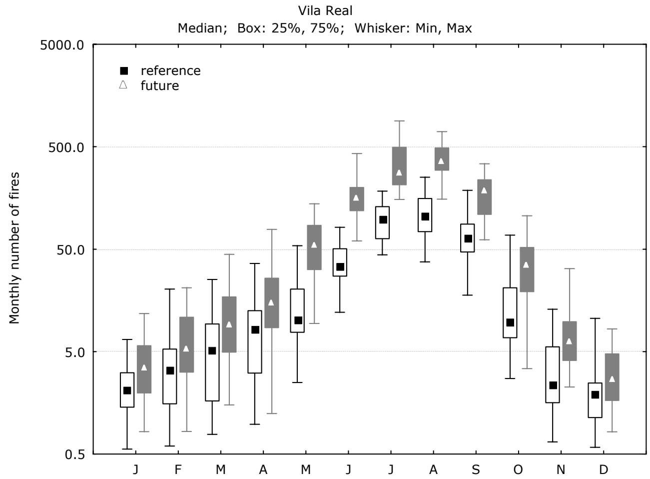
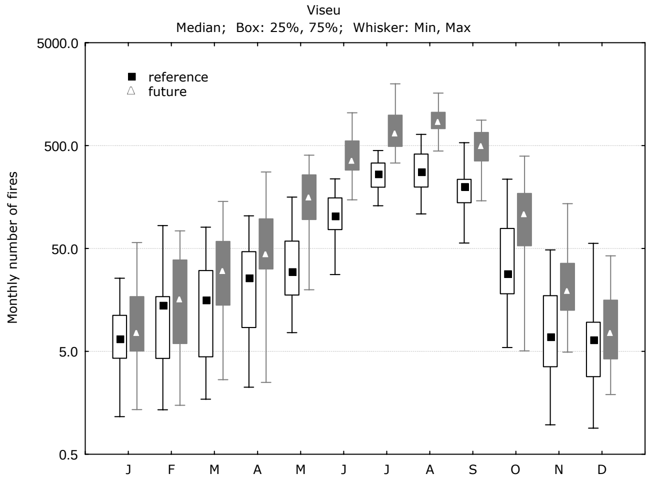
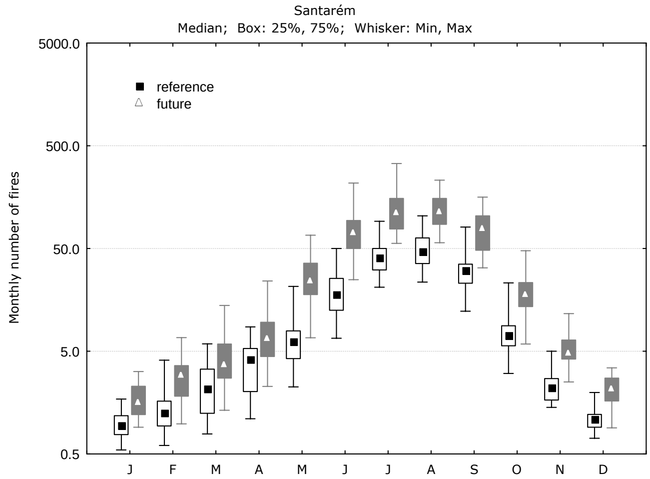


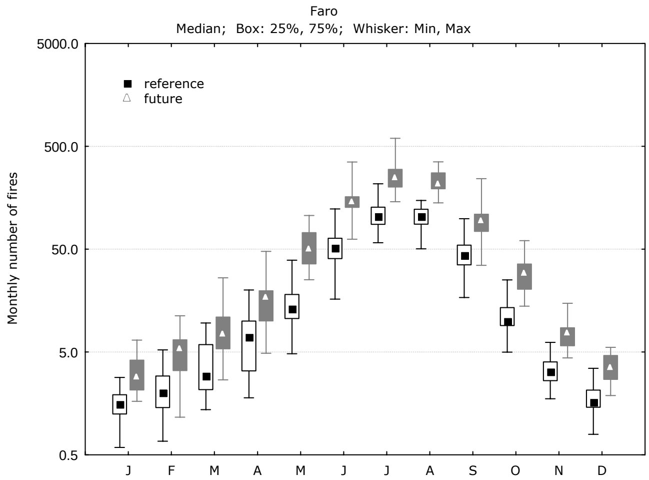

Figure D.1 - Monthly area burned distribution for reference (1961-1990) and future (2071-2100) climate by district.

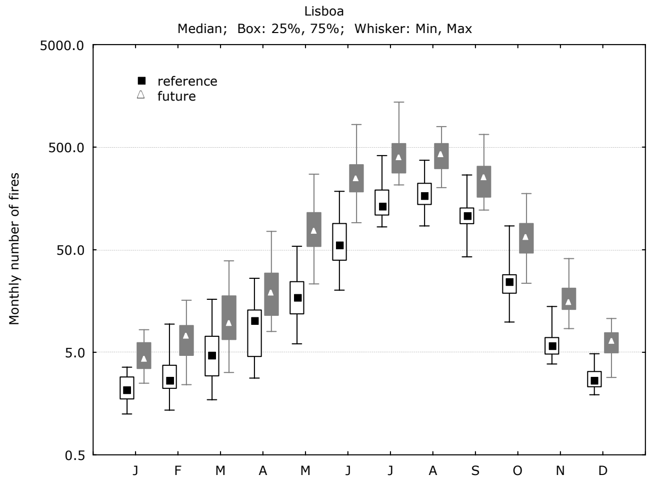

Castelo Branco
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D


Vila Real
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D


Viseu
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D


Santarém
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D


Faro
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D


Lisboa
Median; Box: 25%, 75%; Whisker: Min, Max
reference
future
Monthly number of fires
5000.0
500.0
50.0
5.0
0.5
J F M A M J J A S O N D

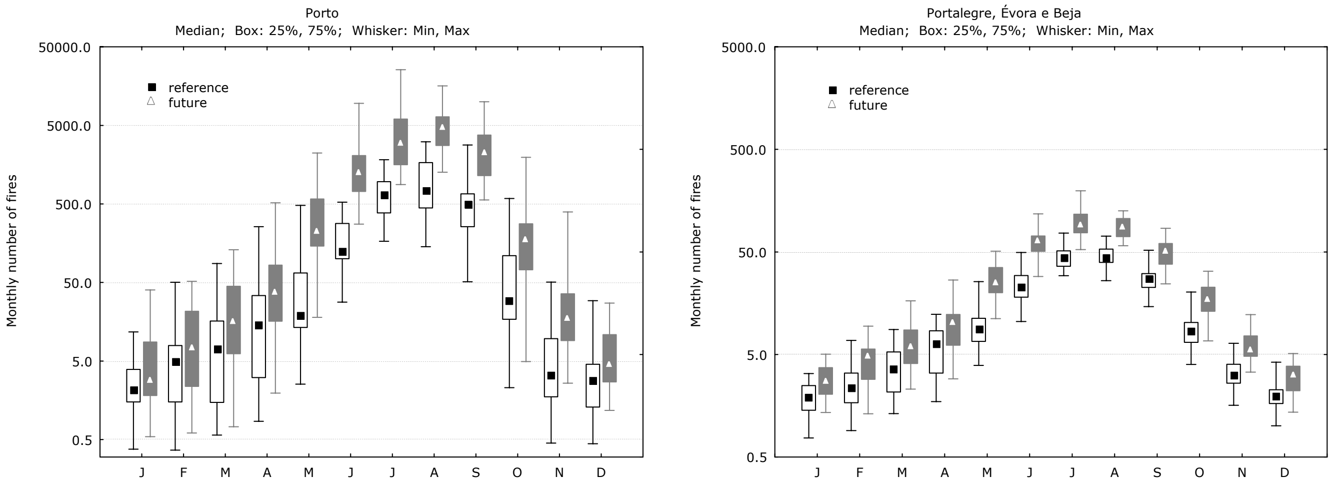



Figure D.2 - Monthly number of fires distribution for reference (1961-1990) and future (2071-2100) climate by district.

# Appendix e

## Appendix E – MM5 outputs over Europe for reference and future climate

Figure E.1 to Figure E.4 depict the monthly averages of boundary layer height, wind speed, relative humidity and temperature over Europe from May to October.

The presented maps exhibit the differences between the future climate (2100) and the reference climate (1990).

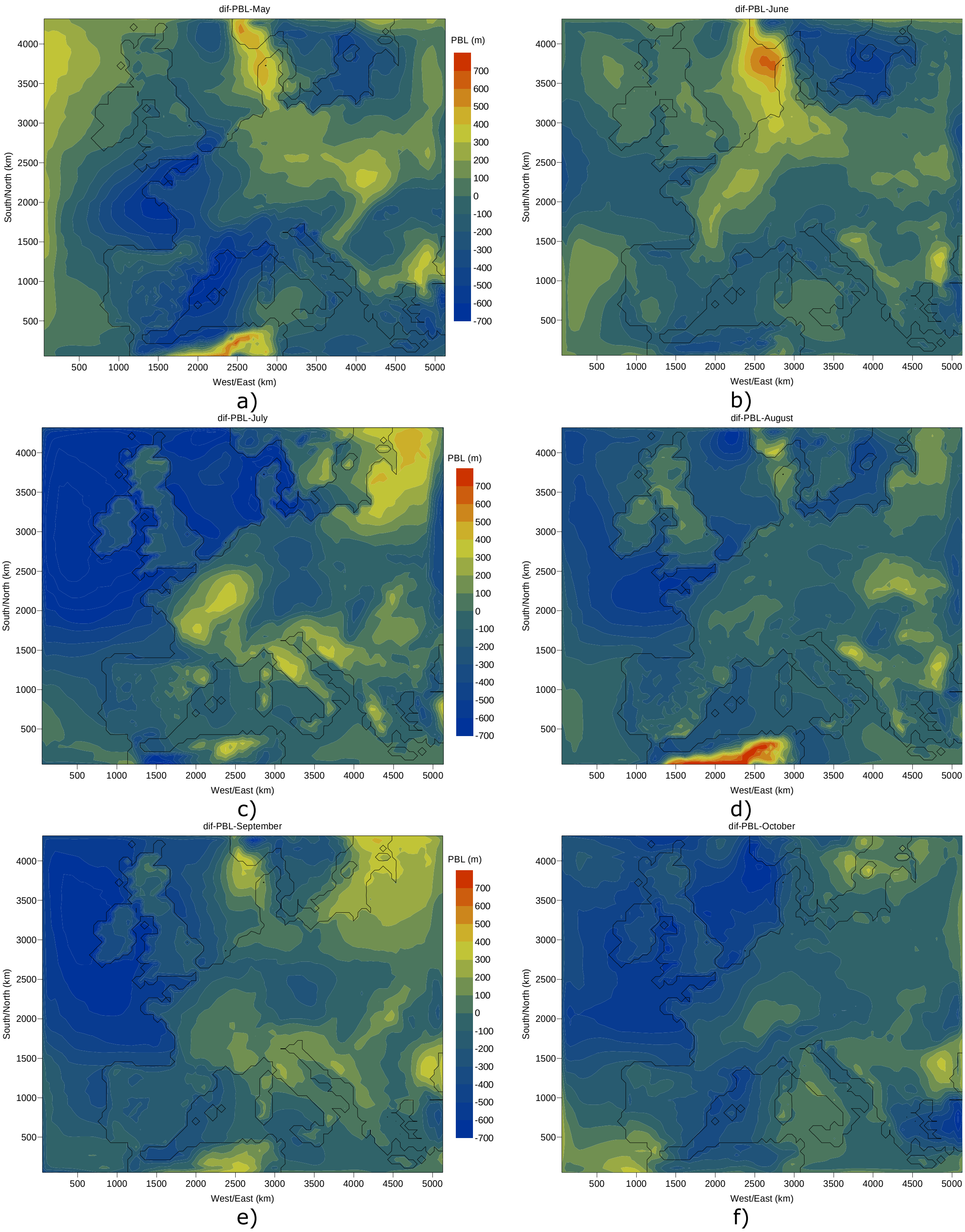



Figure E.1 – Monthly mean boundary layer height differences simulated over Europe with MM5 model between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

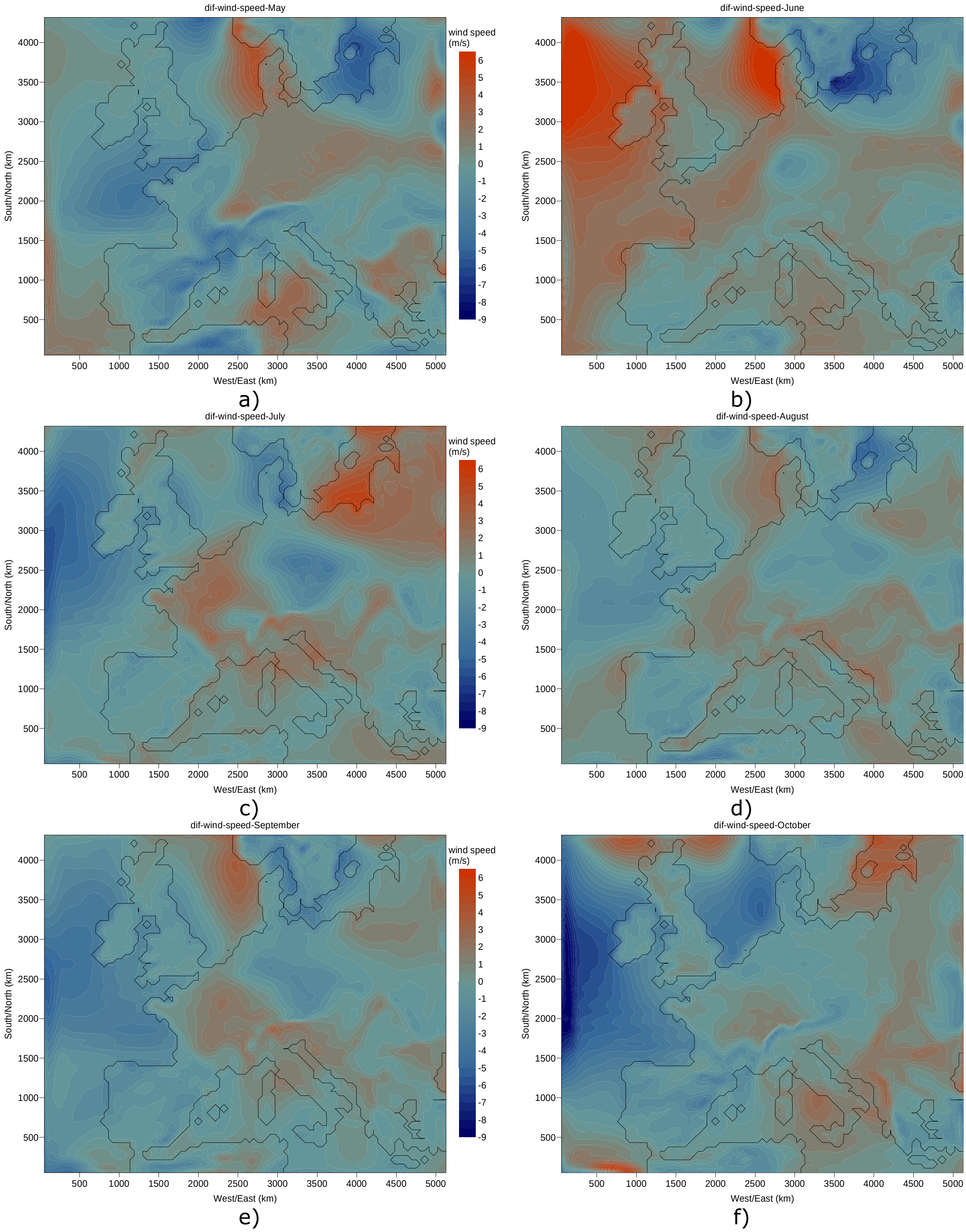



Figure E.2 - Monthly mean wind speed differences simulated over Europe with MM5 model between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

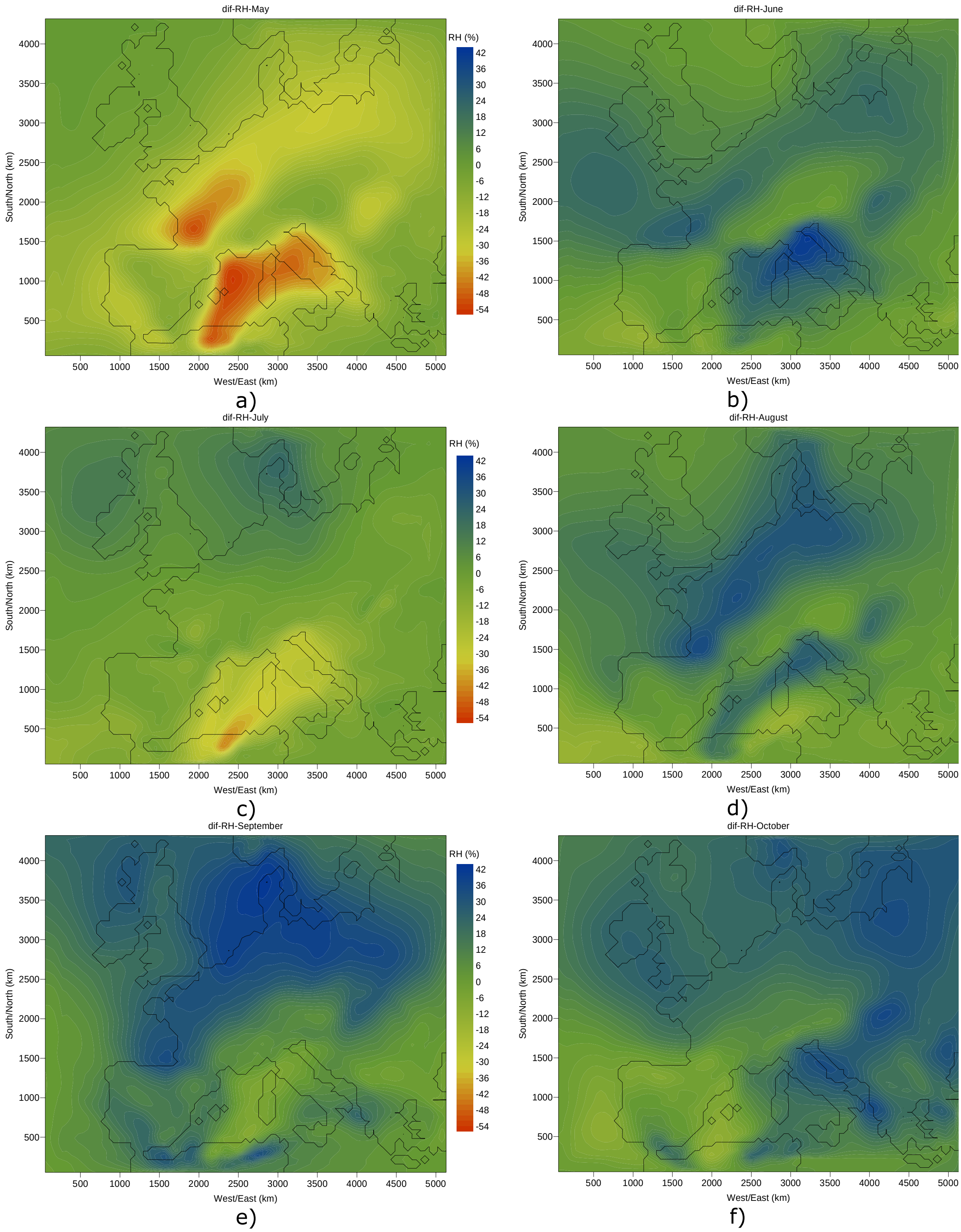



Figure E.3 - Monthly mean relative humidity differences simulated over Europe with MM5 model between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

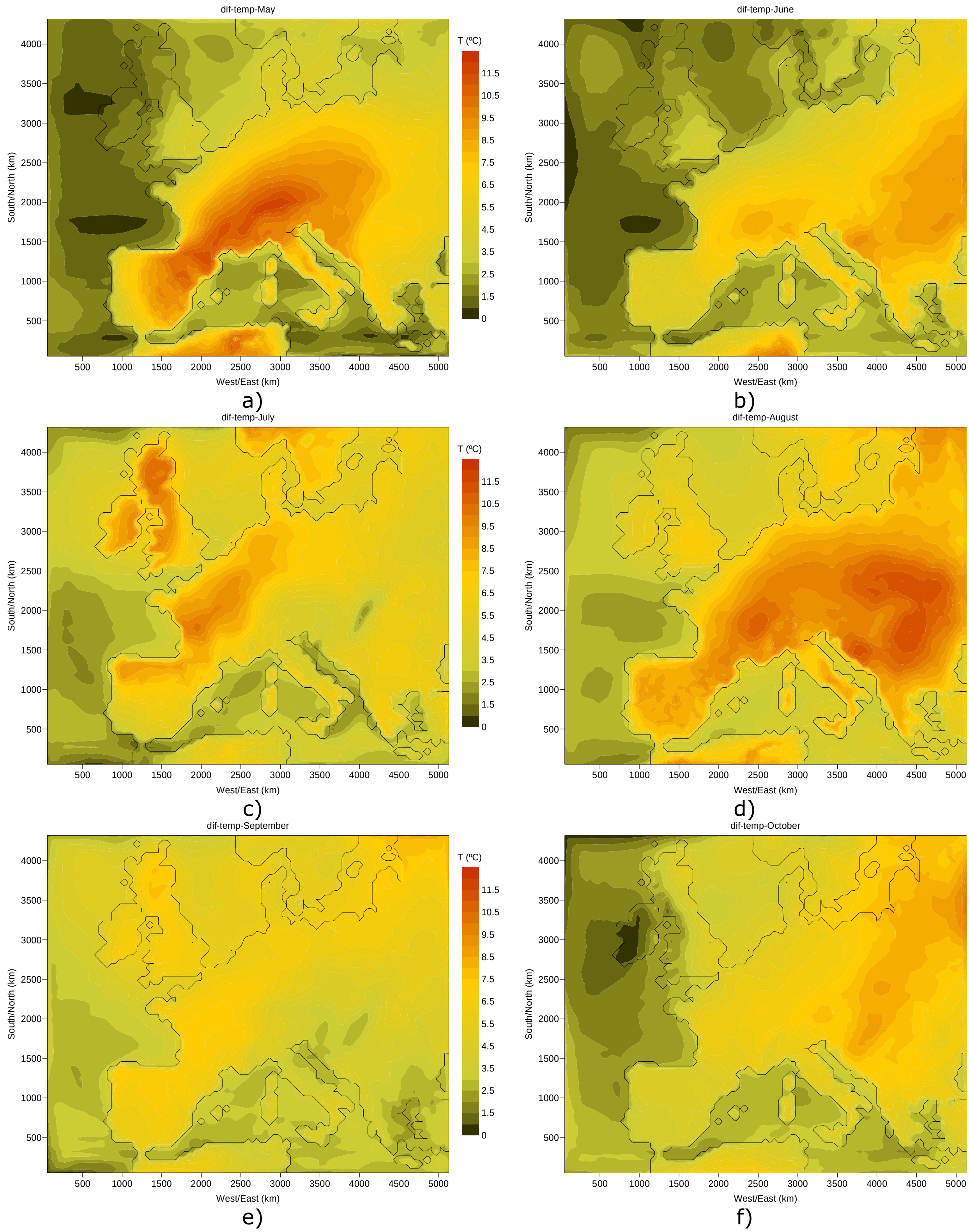



Figure E.4 - Monthly mean surface temperature differences simulated over Europe with MM5 model between 2100 climate and 1990 climate for a) May, b) June, c) July, d) August, e) September, and f) October.

# Appendix f

## Appendix F – $O_3$ and $PM_{10}$ differences between future and reference climate

Figure F.1 shows the monthly ozone averages for May, June and October and Figure F.2 depicts the hourly ozone averages at 9 UTC and 21 UTC for August. The presented maps represent concentrations differences between the future and the reference scenario. On the left it is possible to see only the climate change effect and on the right climate change and future fire emissions are considered.

Figure F.3 presents the monthly $PM_{10}$ averages for May, June and October, considering only climate change impacts and climate change and future forest fire emissions.

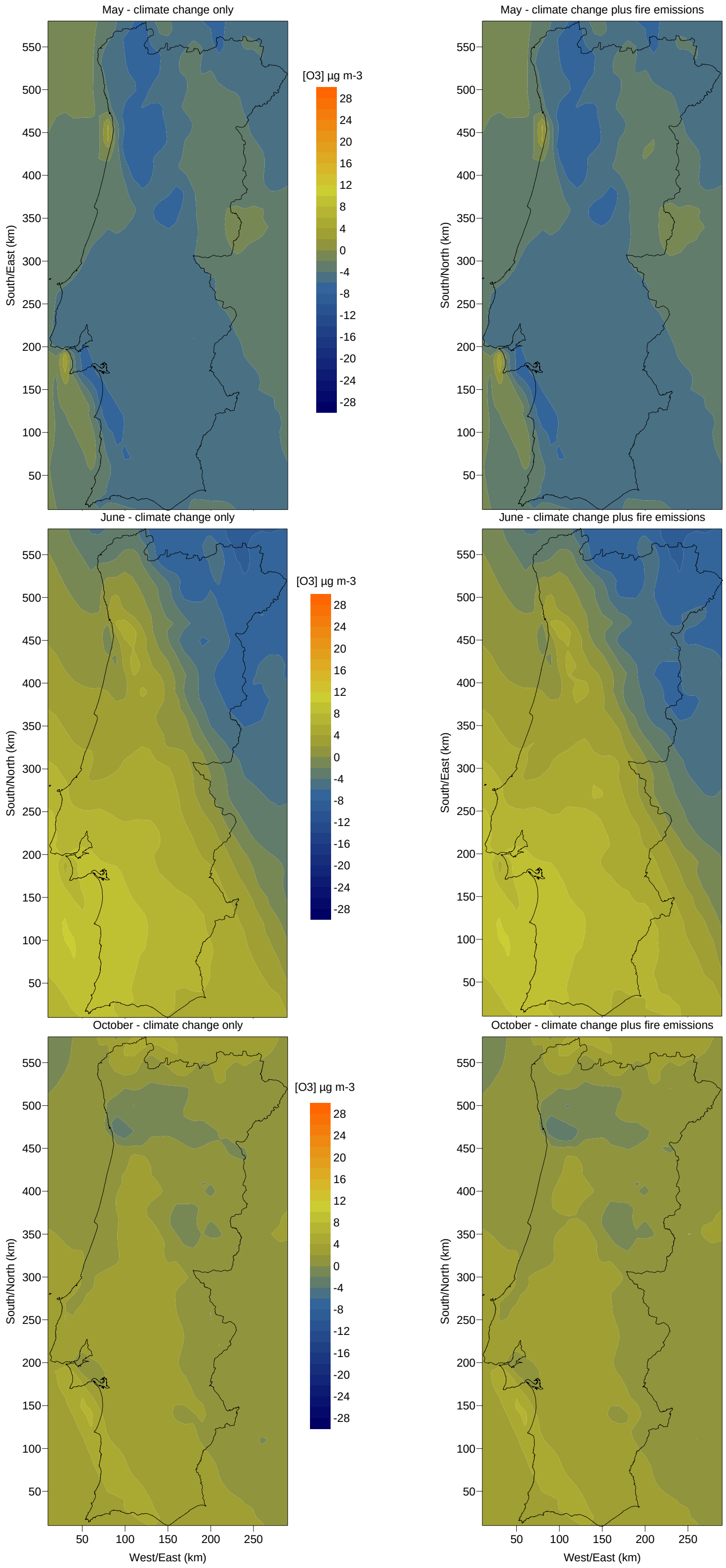



Figure F.1 - Monthly mean surface $O_3$ changes simulated over Portugal considering only climate change (S1 – C1) and climate change and future fire emissions (S2 – C1) for May, June, and October.

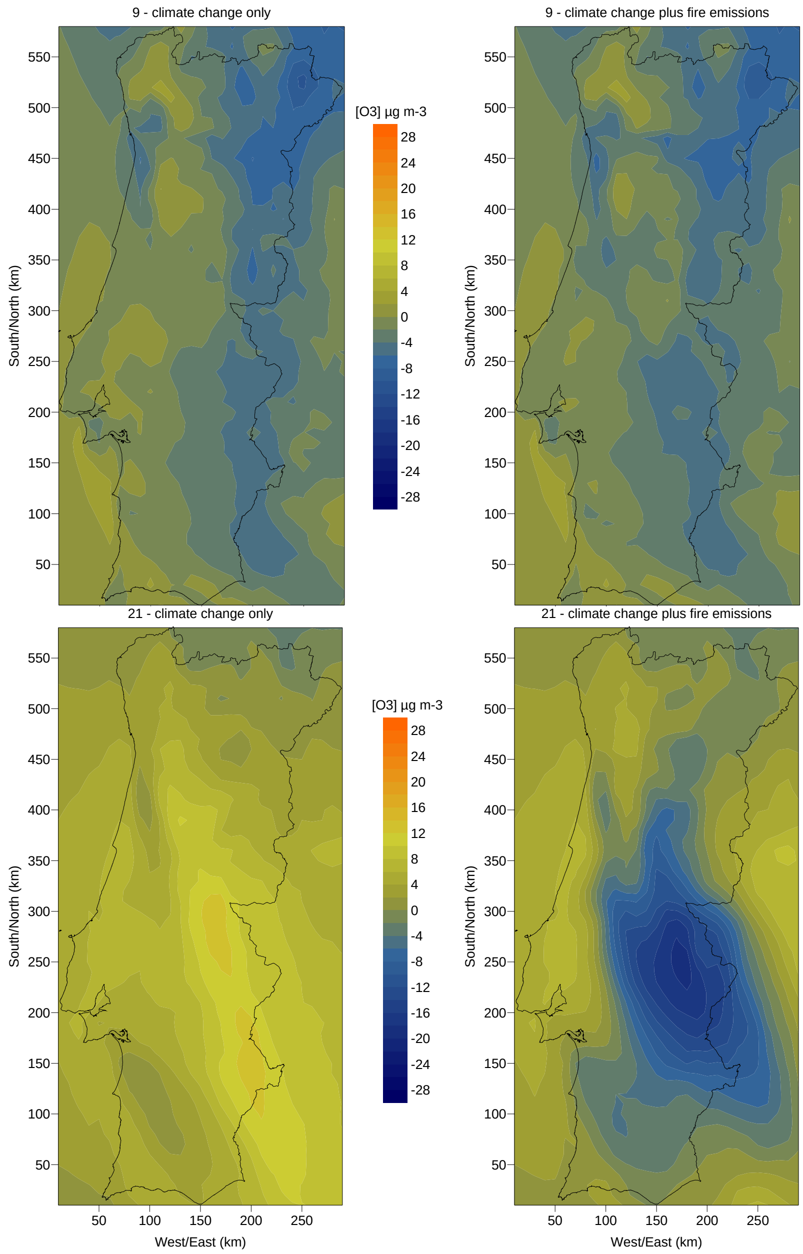



Figure F.2 - Hourly average $O_3$ concentrations for August at 9, and 21 UTC considering climate change only (S1-C1) and climate change and future forest fire emissions (S2-C1).

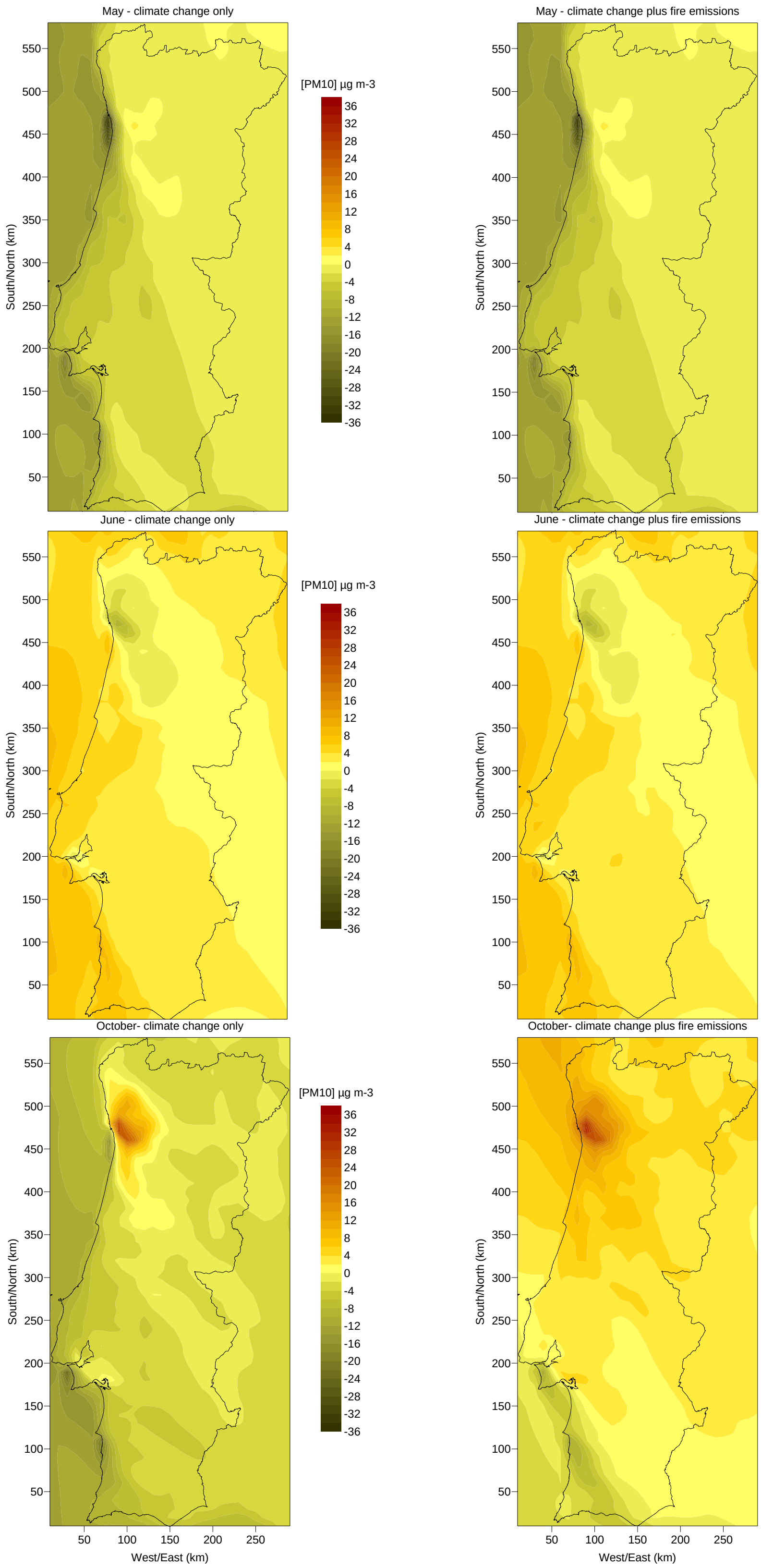



Figure F.3 - Monthly surface $PM_{10}$ concentrations over Portugal considering only climate change (S1 – C1) impacts and climate change and future forest fire emissions (S2 – C1) for May, June, and October.